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# Journal of Research

## of the

## National Bureau of Standards

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## MATHEMATICAL TABLES

A list of the mathematical tables now obtainable from the National Bureau of Standards is printed on page 3 of the Journal cover. New tables will be announced from time to time as they become available.

U. S. Department of Commerce National Bureau of Standards

RESEARCH PAPER RP1444

*Part of Journal of Research of the National Bureau of Standards, Volume 28, January 1942*

# THE TEE-BEND TEST TO COMPARE THE WELDING QUALITY OF STEELS

By George A. Ellinger,
A. G. Bissell,* and Morgan L. Williams

ABSTRACT

A bend test for comparing the welding quality of steels is described in this paper. Specimens of fillet-welded T-sections of a number of low-alloy high-tensile steels were bent in special testing jigs at room temperature and at temperatures as low as −20° F. Several criteria, such as maximum load, angle at maximum load, type and location of fractures, were used to compare the specimens. A special method of statistical analysis, which is described in detail in the paper, was used to evaluate the data and to compare and rate the welding quality of the steels.

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## I. INTRODUCTION

In recent years there has been a marked increase in the use of welded in place of riveted construction, particularly for the fabrication of ships. This change involved more than a simple substitution of one method for another. The design for riveted construction is not necessarily equally suitable for welding, and the most effective use of material in welded construction is obtained only when the requirements for this method are well understood and provided for in the design.

*Bureau of Ships, Navy Department.

Furthermore, all steels or other constructional metals are not equally well adapted to joining by welding. There is no "best" steel for welding nor a "best" welding method or technique, but a best combination of these interrelated factors can be determined for any metal that is weldable. In selecting the metal best adapted to the strength requirements of the design and utility of a structure to be assembled by welding, the welding quality of the metal, within the limitations imposed by the practicability of the welding method, is of prime importance.

With proper attention to design and welding technique, little difficulty need be encountered in welding medium steel by fusion processes.

In 1933, the Bureau of Construction and Repair (now a part of the Bureau of Ships) of the Navy Department and the National Bureau of Standards started a cooperative investigation of the welding quality of steels considered suitable for naval construction. Particular attention was to be given to "high tensile" low-alloy steels, of which numerous varieties and types have since been announced by manufacturers.[1] [2] [3] [4] [5] A further requirement was that strong ductile joints should be obtained by the electric-arc welding process with low-carbon steel, Navy Grade EA electrodes, and without preheating or postheating.

The strength properties of welded joints can readily be determined by well-established methods. The relationships between "ductility" in a welded joint and the welding quality of the steel were not clearly defined, and methods for making the mechanical tests of a specimen from a welded joint to evaluate ductility were not well established. It was considered, however, that some form of bend test would be the most nearly suitable for this purpose.

It is generally agreed that ability to bend in the plastic-deformation range is evidence of ductility in a metal, whether in a weld or in an otherwise fabricated form. The full ductility of a metal may not be realized in a bend test of a specimen because of local stress conditions peculiar to the geometrical shape of the specimen. Free bends and guided bends in jigs have been used widely for face, root, or side bends of butt-welded joints. Often the faces of the welds are machined for these types of test.

For the purpose of this investigation, it was decided that the most informative results would be obtained from a guided bend test, in a jig, of a double-fillet T–welded specimen, without removing any metal from the face of the welds. Justification for this decision was had in the fact that this type of joint is one of the most widely used in ship-hull construction, and furthermore, the ability of the specimen to withstand bending distortion in the welded areas, without rupture, is an indication that such a joint can absorb a proportionate share of the distortion of the structure as a whole.

Ability to withstand severe distortions without premature or brittle-type ruptures, particularly in the joints, is a highly desirable, in fact a necessary, feature in ship-hull structures. It is not to be expected,

[1] H. W. Gillett, *Trends in the metallurgy of low-alloy, high-strength structural steels*, Role of Metals in New Transportation Symposium, Metals Tech. **3**, 40 (1936).
[2] Edwin F. Cone, *Carbon and low-alloy steels*, Symposium on High Strength Constructional Metals, p. 1 (Am. Soc. Testing Materials, Philadelphia, Pa.).
[3] *Low-alloy, high strength structural steels—An extended abstract*, Metals & Alloys **7**, 77 (1936).
[4] *The present status of the low-alloy, high-strength steels—A survey*, Metals & Alloys **9**, 243 (1938).
[5] *The present status of the low-alloy, high-strength steels—A survey*, Metals & Alloys **13**, 273 (1941).

however, that the maximum angle of bend, or any other numerical value obtained from a bend test on a welded joint, is a direct measure of the amount of distortion the joint can withstand in the assembled structure. These values were used in this investigation as a means of comparison, on a common basis, of the welding qualities of a number of structural steels, as shown by certain properties related to the service requirements of the welds.

This paper describes the steels and preparation of the welded specimens and the procedure for making the bend tests, and describes and discusses the methods for evaluating the welding quality of the steels from the results of the bend tests and other metallurgical and mechanical properties of the welds and of the steels themselves.

## II. MATERIALS

The steels to be tested included several medium- and low-alloy "high tensile" steels available at that time. The following tensile properties were desired for the steels:

| | |
|---|---|
| Yield point, minimum | 50,000 lb/in.² |
| Tensile strength, minimum | 70,000 lb/in.² |
| Elongation in 8 in., minimum | 20 percent. |

Each steel was to be secured in three thicknesses of plates, ¼, ½, and ¾ in., and was to be welded in the as-rolled condition and after normalizing at 1,650° F. for 1 hour. It was also desired that all of the plates of each steel should be rolled from the same heat.

The chemical compositions of the steels are given in table 1.

TABLE 1.—*Chemical composition of the steels* [a]

| Steel | Thickness | Percentage of— | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | P | S | Si | Ni | Cr | V | Mo | Cu |
| | *In.* | | | | | | | | | | |
| 138 | ¼ | 0.14 | 0.46 | 0.014 | 0.025 | 0.18 | ..... | ..... | ..... | ..... | 0.23 |
| | ½ | .14 | .46 | .013 | .024 | .17 | ..... | ..... | ..... | ..... | .22 |
| | ¾ | .14 | .46 | .015 | .025 | .17 | ..... | ..... | ..... | ..... | .23 |
| 139 | ¼ | .20 | .69 | .019 | .036 | .18 | ..... | ..... | ..... | ..... | .20 |
| | ½ | .20 | .70 | .022 | .036 | .17 | ..... | ..... | ..... | ..... | .20 |
| | ¾ | .19 | .68 | .020 | .034 | .18 | ..... | ..... | ..... | ..... | .23 |
| 140 | ¼ | .26 | .66 | .014 | .030 | .17 | ..... | ..... | ..... | ..... | .22 |
| | ½ | .26 | .67 | .015 | .031 | .17 | ..... | ..... | ..... | ..... | .23 |
| | ¾ | .26 | .66 | .013 | .030 | .17 | ..... | ..... | ..... | ..... | .24 |
| 141 | ¼ | .17 | .44 | .019 | .030 | .13 | 0.07 | ..... | ..... | 0.09 | .16 |
| | ½ | .20 | .70 | .017 | .032 | .19 | .08 | ..... | ..... | .09 | .19 |
| | ¾ | .20 | .70 | .017 | .032 | .19 | .08 | ..... | ..... | .09 | .19 |
| 143 | ¼ | .14 | .61 | .011 | .035 | .19 | 1.28 | 0.06 | 0.09 | ..... | .04 |
| | ½ | .14 | .62 | .012 | .035 | .19 | 1.30 | .06 | .09 | ..... | .04 |
| | ¾ | .14 | .61 | .011 | .035 | .19 | 1.28 | .06 | .09 | ..... | 04 |
| 144 | ¼ | .18 | .99 | .017 | .030 | .17 | ..... | .05 | .07 | ..... | .16 |
| | ½ | .17 | 1.25 | .033 | .028 | .21 | ..... | ..... | .12 | ..... | .15 |
| | ¾ | .17 | 1.25 | .031 | .027 | .21 | ..... | ..... | .12 | ..... | .15 |
| 145 | ¼ | .10 | .75 | .011 | .027 | .17 | .26 | ..... | ..... | .46 | .11 |
| | ½ | .08 | .76 | .011 | .028 | .15 | .27 | ..... | ..... | .44 | .10 |
| | ¾ | .17 | .83 | .021 | .030 | .24 | .09 | ..... | ..... | .44 | .12 |
| 146 | ¼ | .10 | .44 | .012 | .023 | .16 | 1.92 | ..... | ..... | ..... | 1.06 |
| | ½ | .09 | .42 | .014 | .019 | .17 | 1.94 | ..... | ..... | ..... | 1.00 |
| | ¾ | .10 | .38 | .015 | .019 | .16 | 1.90 | ..... | ..... | ..... | 1.01 |

[a] The chemical analyses were made at the Material Laboratory, Naval Gun Factory, Washington, D. C.

TABLE 1.—*Chemical composition of the steels—Continued*

| Steel | Thickness | Percentage of— | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | P | S | Si | Ni | Cr | V | Mo | Cu |
| | *In.* | | | | | | | | | | |
| 147 | 1/4 | 0.11 | 0.57 | 0.015 | 0.023 | 0.15 | 2.03 | 0.02 | ..... | ..... | 1.08 |
| | 1/2 | .14 | .57 | .014 | .025 | .14 | 1.99 | .02 | ..... | ..... | 1.02 |
| | 3/4 | .14 | .57 | .014 | .024 | .15 | 1.95 | .02 | ..... | ..... | 1.08 |
| 148 | 1/4 | .11 | .76 | .106 | .026 | .02 | 0.71 | ..... | ..... | 0.11 | 1.74 |
| | 1/2 | .09 | .75 | .097 | .024 | .06 | .72 | ..... | ..... | .10 | 1.63 |
| | 3/4 | .08 | .76 | .101 | .029 | .06 | .68 | ..... | ..... | .11 | 1.76 |
| 149 | 1/4 | .10 | .66 | .126 | .023 | .16 | .60 | ..... | ..... | ..... | 1.00 |
| | 1/2 | .09 | .56 | .112 | .023 | .17 | .59 | ..... | ..... | ..... | 1.04 |
| | 3/4 | .11 | .56 | .109 | .023 | .17 | .60 | ..... | ..... | ..... | 1.16 |
| 150 | 1/4 | .14 | .59 | .014 | .026 | .16 | 2.32 | ..... | ..... | .12 | 0.13 |
| | 1/2 | .16 | .59 | .014 | .026 | .18 | 1.90 | ..... | ..... | .10 | .14 |
| | 3/4 | .19 | .54 | .014 | .044 | .18 | 2.04 | ..... | ..... | .07 | .14 |
| 157 | 1/4 | .15 | .98 | .015 | .026 | .21 | .06 | .05 | 0.09 | .10 | .10 |
| | 1/2 | .16 | .98 | .016 | .027 | .21 | .06 | .05 | .09 | .10 | .18 |
| | 3/4 | .15 | .96 | .015 | .028 | .22 | .07 | .05 | .09 | .10 | .10 |
| 161 | 1/4 | .14 | .45 | .082 | .013 | .02 | 1.82 | .14 | ..... | ..... | .56 |
| | 1/2 | .14 | .45 | .079 | .015 | .01 | 1.87 | .14 | ..... | ..... | .58 |
| | 3/4 | .14 | .47 | .090 | .016 | .01 | 1.90 | .16 | ..... | ..... | .54 |
| 163 | 1/4 | .10 | .72 | .011 | .021 | .01 | 1.30 | ..... | ..... | .12 | 1.58 |
| | 1/2 | .10 | .70 | .011 | .021 | .01 | 1.30 | ..... | ..... | .12 | 1.50 |
| 166 | 1/2 | .09 | .59 | .012 | .018 | .003 | 1.28 | ..... | ..... | .11 | 1.15 |
| 168 | 1/4 | .09 | .62 | .012 | .024 | .02 | 1.37 | ..... | ..... | .11 | 1.08 |
| | 1/2 | .07 | .60 | .011 | .023 | .02 | 1.36 | ..... | ..... | .09 | 1.03 |
| | | | | | | | | | | Zr | |
| 201 | [b] 1/4 | .13 | .66 | .027 | .023 | .73 | 0.10 | .63 | ..... | .14 | 0.19 |
| | [c] 1/4 | .12 | .70 | .019 | .025 | .77 | .10 | .57 | ..... | .13 | .20 |
| | [b] 1/2 | .13 | .67 | .020 | .020 | .84 | .07 | .50 | ..... | .11 | .09 |
| | [c] 1/2 | .13 | .69 | .019 | .027 | .87 | .14 | .64 | ..... | .10 | .25 |

[b] Plates as rolled
[c] Plates normalized.

The different thicknesses of steels 141, 144, 145, 148, 149, 150, and 201 were definitely rolled from different heats. The different thicknesses of the remaining steels were probably rolled from single heats.

Tensile properties of the steels are given in table 2.

TABLE 2.—*Tensile properties of the steels* [a]

| Steel | Thickness | Yield point [b] | | Tensile strength | | Elongation (8 in.) | |
|---|---|---|---|---|---|---|---|
| | | As rolled | Normalized | As rolled | Normalized | As rolled | Normalized |
| | *in.* | *lb/in.²* | *lb/in.²* | *lb/in.²* | *lb/in.²* | *Percent* | *Percent* |
| 138 | 1/4 | 41,700 | 37,600 | 62,400 | 59,900 | 32.5 | 34.1 |
| | 1/2 | 40,800 | 36,100 | 61,100 | 57,900 | 34.7 | 36.7 |
| | 3/4 | 37,700 | 42,600 | 61,300 | 60,300 | 33.8 | 37.0 |
| 139 | 1/4 | 52,800 | 46,800 | 73,600 | 66,600 | 28.3 | 25.0 |
| | 1/2 | 52,800 | 46,600 | 73,700 | 67,800 | 23.3 | 32.4 |
| | 3/4 | 44,800 | 45,400 | 72,100 | 67,200 | 35.0 | 30.5 |
| 140 | 1/4 | 52,200 | 43,400 | 78,800 | 74,400 | 29.5 | 46.2 |
| | 1/2 | 47,500 | 41,400 | 73,700 | 70,400 | 26.2 | 30.3 |
| | 3/4 | 47,700 | 42,600 | 74,900 | 71,400 | ..... | 32.5 |
| 141 | 1/4 | 46,800 | 37,900 | 65,900 | 60,100 | 27.8 | 27.8 |
| | 1/2 | 51,500 | 48,100 | 73,000 | 68,800 | 25.0 | 26.8 |
| | 3/4 | 46,800 | 46,400 | 73,600 | 70,100 | 28.4 | 29.3 |

[a] Tensile-property tests were made at the Physical Laboratory, Model Basin, Washington, D. C.
[b] Yield point was determined by "drop of the beam" of the testing machine.

TABLE 2.—*Tensile properties of the steels*—Continued

| Steel | Thickness | Yield point | | Tensile strength | | Elongation (8 in.) | |
|---|---|---|---|---|---|---|---|
| | | As rolled | Normalized | As rolled | Normalized | As rolled | Normalized |
| | *in.* | *lb/in.²* | *lb/in.²* | *lb/in.²* | *lb/in.²* | *Percent* | *Percent* |
| 143 | ¼ | 65,700 | 45,200 | 80,200 | 62,700 | 18.5 | 29.1 |
| | ½ | 61,800 | 45,800 | 79,000 | 63,600 | 20.9 | 28.4 |
| | ¾ | 58,300 | 47,300 | 76,600 | 65,000 | 22.5 | 28.5 |
| 144 | ¼ | 64,200 | 49,000 | 85,900 | 71,100 | 22.3 | 26.0 |
| | ½ | 64,000 | ..... | 82,700 | ..... | 22.0 | ..... |
| | ¾ | 60,100 | ..... | 84,400 | ..... | 23.6 | ..... |
| 145 | ¼ | ..... | 35,200 | 81,000 | 60,000 | 15.3 | 27.7 |
| | ½ | 43,500 | 40,200 | 65,600 | 66,400 | 25.8 | 23.8 |
| | ¾ | 50,900 | 44,000 | 79,700 | 75,000 | 24.2 | 24.6 |
| 146 | ¼ | 59,000 | 57,700 | 71,100 | 68,500 | 27.7 | 28.3 |
| | ½ | 53,300 | 55,900 | 68,300 | 67,700 | 26.6 | 28.1 |
| | ¾ | 49,200 | 50,400 | 67,000 | 66,100 | 27.4 | 28.5 |
| 147 | ¼ | 59,900 | 60,200 | 75,300 | 73,600 | 26.5 | 28.2 |
| | ½ | 53,900 | 58,400 | 72,900 | 72,500 | 25.6 | 27.0 |
| | ¾ | 49,700 | 57,600 | 71,600 | 72,300 | 26.3 | 26.5 |
| 148 | ¼ | ..... | 59,900 | 81,400 | 80,500 | 20.4 | 20.8 |
| | ½ | 57,800 | 53,800 | 81,000 | 77,200 | 18.1 | 21.3 |
| | ¾ | 54,500 | 61,900 | 82,700 | 79,600 | 14.3 | 19.1 |
| 149 | ¼ | 59,700 | 58,600 | 69,700 | 73,200 | 25.2 | 27.7 |
| | ½ | 58,300 | 57,000 | 72,000 | 71,100 | 25.0 | 22.6 |
| | ¾ | 54,700 | 53,300 | 70,300 | 69,600 | 28.3 | 28.6 |
| 150 | ¼ | 62,600 | 51,400 | 75,100 | 69,000 | 24.0 | 24.8 |
| | ½ | 51,100 | 47,700 | 71,200 | 68,900 | 26.5 | 27.4 |
| | ¾ | 47,300 | 48,200 | 72,400 | 71,500 | 27.1 | 28.2 |
| 157 | ¼ | 75,600 | 57,800 | 90,600 | 62,300 | 19.6 | 29.3 |
| | ½ | 61,700 | 47,000 | 81,800 | 64,100 | 19.4 | 28.3 |
| | ¾ | ..... | 46,600 | 80,000 | 65,200 | 21.3 | 28.5 |
| 161 | ¼ | 55,500 | ..... | 72,400 | ..... | 25.6 | ..... |
| | ½ | 66,200 | ..... | 71,000 | ..... | 25.9 | ..... |
| | ¾ | 62,600 | ..... | 70,200 | ..... | 28.9 | ..... |
| 163 | ¼ | 74,700 | 63,600 | 86,300 | 65,400 | 18.8 | 23.4 |
| | ½ | 60,900 | 41,800 | 78,600 | 53,900 | 20.6 | 24.3 |
| 166 | ½ | 50,800 | ..... | 68,600 | ..... | 27.0 | ..... |
| 168 | ¼ | ..... | ..... | 70,400 | 68,200 | 23.8 | 24.4 |
| | ½ | 60,000 | 48,000 | 73,600 | 66,100 | 19.2 | 26.7 |
| 201 | ¼ | 55,400 | 51,300 | 77,800 | 76,200 | 24.0 | 26.0 |
| | ½ | 51,200 | 54,300 | 78,100 | 78,500 | 29.0 | 29.0 |

In the as-rolled condition, steels 139, 143, 144, 147, 149, 150, 161, and 201 complied with all of the tensile property requirements, and in the normalized condition, only steels 147, 148, 149, and 201 met these requirements.

The entire schedule of bend tests was not completed on all of the steels. The results of detailed studies of the nonmetallic inclusions, vacuum-fusion and residue analyses, and microstructural features are presented on eight steels only, 141, 144, 145, 146, 147, 148, 149, and 150. Five of these steels were carried through the entire bend-test schedule. The bend-test schedule was completed also on one plain carbon steel, 139.

Typical microstructures in the unetched condition, showing nonmetallic inclusions are shown in figure 1. The inclusions were of the following types:

| *Steel No.* | *Types of inclusions* |
|---|---|
| 141 | Some $Al_2O_3$, silicates, sulfides. No complex inclusions. |
| 144 | Few silicates, numerous sulfides, simple and complex. |
| 145 | Few silicates, dark complex oxides, large complex inclusions with acicular structures. |
| 146 | Few sulfides, complex oxides. |
| 147 | Few sulfides, complex oxides, very few silicates. |
| 148 | Many $Al_2O_3$ inclusions, complex oxides, silicates, sulfides. |
| 149 | Few complex oxides, sulfides. |
| 150 | Complex inclusions, few silicates. |

Steels 141, 144, 145, and 148 were very dirty, while steels 146, 147 149, and 150 were clean.

The amounts of oxygen, nitrogen, and hydrogen in these steels were determined by vacuum-fusion analyses of samples from the ½-in. plates. The results are given in table 3.

TABLE 3.—*Results of vacuum fusion analyses*

| Steel | Oxygen | Nitrogen | Hydrogen | Steel | Oxygen | Nitrogen | Hydrogen |
|---|---|---|---|---|---|---|---|
| | *Percent* | *Percent* | *Percent* | | *Percent* | *Percent* | *Percent* |
| 141 | 0.012 | 0.004 | None | 147 | 0.005 | 0.005 | 0.0002 |
| 144 | .005 | .005 | None | 148 | .037 | .005 | ---------- |
| 145 | .039 | .004 | None | 149 | .005 | .004 | .0001 |
| 146 | .005 | .005 | None | 150 | .010 | .004 | None |

Steels 145 and 148 were very high in oxygen, and there was more oxygen in steel 141 than is usually found in clean steels. It will be noted by comparing these results with the microstructures that oxygen was highest in the dirty steels, 141, 145, and 148. Steel 144 also contained numerous inclusions, but these were largely sulfides. Most of the inclusions in steel 148 were $Al_2O_3$, and most of those in 145 were complex oxides, probably mixtures of FeO-MnO. There were some $Al_2O_3$ and other oxides and silicates in steel 141.

Residue analyses for $Al_2O_3$ were made on steels having the highest oxygen contents. Results of these analyses are given in table 4.

TABLE 4.—*Results of residue analyses*

| Steel | Alumina (residue) | Oxygen as $Al_2O_3$ (calculated) | Oxygen as other constituents (calculated) |
|---|---|---|---|
| | *Percent* | *Percent* | *Percent* |
| 141 | 0.021 | 0.010 | 0.002 |
| 145 | .001 | Trace | .039 |
| 148 | .071 | .033 | .004 |

The results of these analyses confirm the microscopic study of the inclusions, in that most of the oxygen in steels 141 and 148 was present as $Al_2O_3$ while that in steel 145 was in the form of other oxides, probably FeO-MnO.

Typical microstructures of the ½-in. plate metals, as-rolled and after normalizing at 1,650° F for 1 hour, are shown in figures 2 and 3. In

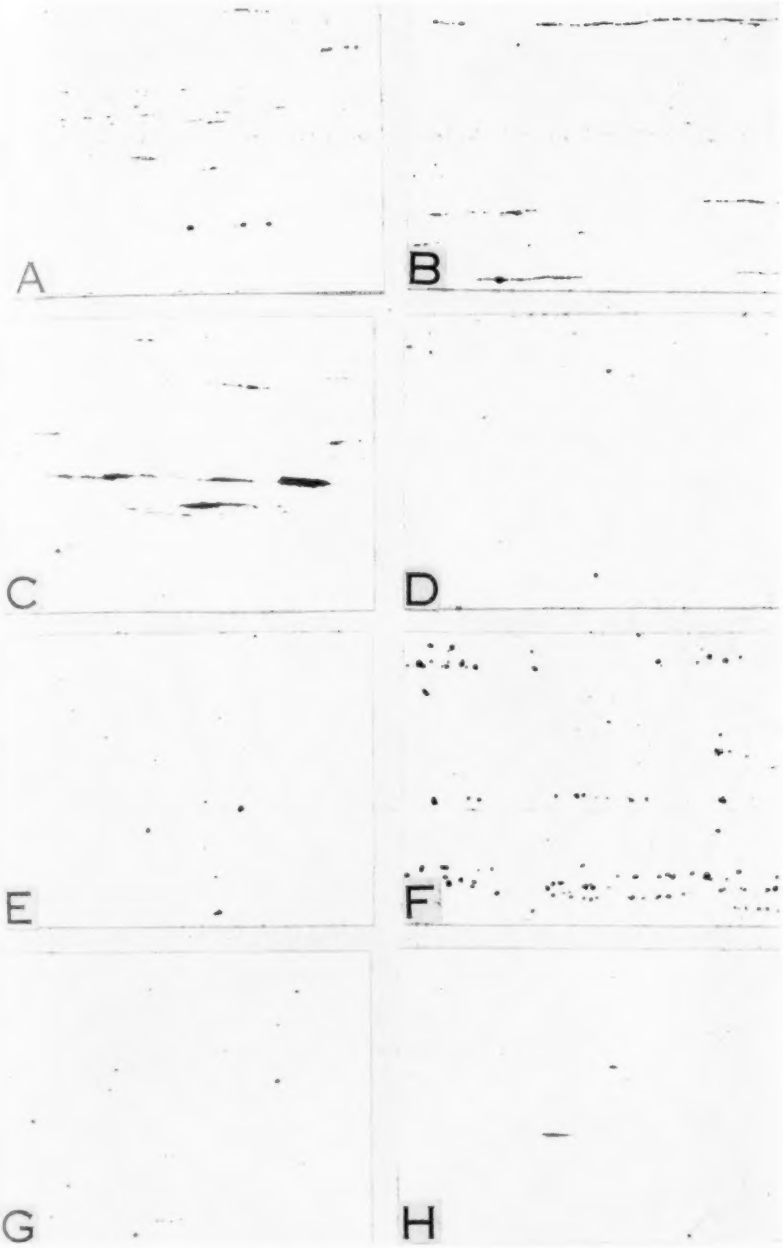


FIGURE 1.—*Nonmetallic inclusions; ½-in. plates; unetched; ×100.*

*A*, Steel 141, manganese-silicon.
*B*, Steel 144, manganese-vanadium.
*C*, Steel 145, manganese-molybdenum.
*D*, Steel 146, copper-nickel.
*E*, Steel 147, copper-nickel.
*F*, Steel 148, copper-nickel-molybdenum.
*G*, Steel 149, copper-nickel-phosphorus.
*H*, Steel 150, 2½ percent nickel.

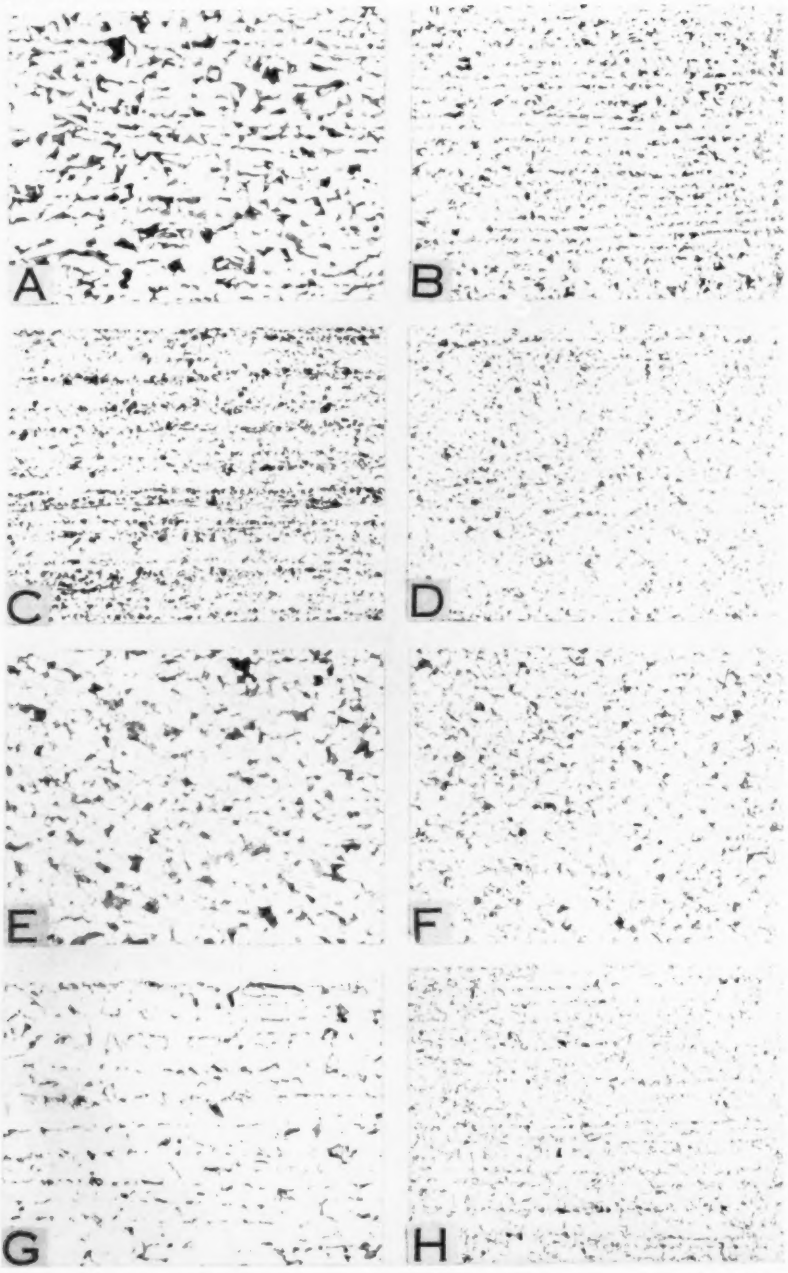


FIGURE 2.—*Typical microstructures; ½-in. plates; etchant, 1 percent nital; ×100.*

*A*, Steel 141, manganese-silicon, as-rolled.
*B*, Steel 141, manganese-silicon, normalized.
*C*, Steel 144, manganese-vanadium, as-rolled.
*D*, Steel 144, manganese-vanadium, normalized.
*E*, Steel 145, manganese-molybdenum, as-rolled.
*F*, Steel 145, manganese-molybdenum, normalized.
*G*, Steel 146, copper-nickel, as-rolled.
*H*, Steel 146, copper-nickel, normalized.

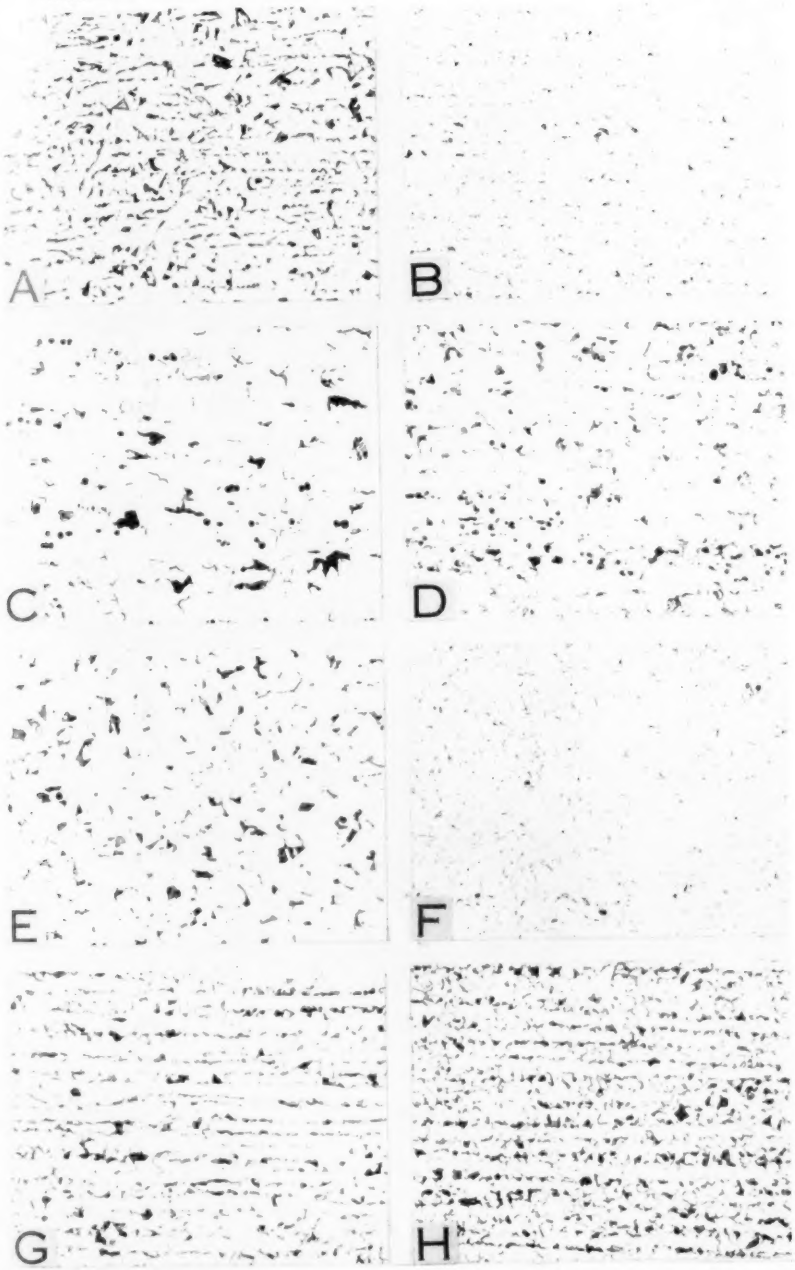


FIGURE 3.—*Typical microstructures; ½-in. plates; etchant, 1 percent nital; ×100.*

*A*, Steel 147, copper-nickel, as-rolled.
*B*, Steel 147, copper-nickel, normalized.
*C*, Steel 148, copper-nickel-molybdenum, as-rolled.
*D*, Steel 148, copper-nickel-molybdenum, normalized.
*E*, Steel 149, copper-nickel-phosphorus, as-rolled.
*F*, Steel 149, copper-nickel-phosphorus, normalized.
*G*, Steel 150, 2½ percent nickel, as-rolled.
*H*, Steel 150, 2½ percent nickel, normalized.

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the as-rolled condition, steels 141, 144, 146, 147, and 150 contained some banded structure. After normalizing, some banding was found in steels 141, 146, 147, and 150, indicating that chemical segregation was responsible for the banded structure in these steels. However, the banding found in steel 144 had largely disappeared after normalizing, indicating that this steel had been finished "cold" in rolling.

While microstructures from ½-in. plates only are shown in this report, specimens from the ¼- and ¾-in. plates were also examined. In general, in the as-rolled condition, the thinner plates had smaller ferrite grain sizes than the thicker plates, due to the additional working which they received in rolling. After normalizing, the grain sizes for the different thicknesses of plates were more nearly uniform.

The austenitic grain size and grain-coarsening temperature were determined for some of the steels by a gradient-quenching method proposed by Vilella and Bain.[6] Most austenitic grain size studies have been made on specimens carburized at some selected temperature (usually 1,700° F) for 8 hours or more. There have been objections to this procedure due to the high temperature, the long time of heating required, and to the possible introduction of impurities or foreign material, which might have a significant effect on the grain size of a steel. In the gradient-quenching method about ½ in. of the length of the specimen (1½ in. long by ¼ in. wide by the full plate thickness) was quenched from a desired temperature into a brine solution. The remainder of the length was allowed to cool in air above the brine.

The quenched end was composed of martensite and the air-cooled end of pearlite. At some point in the quenched end of the specimen, the critical cooling rate for the steel was exceeded and fine pearlite was formed around the austenitic grains, outlining them with black envelopes. In the air-cooled end, the grains were outlined by proeutectoid ferrite. This method was considered to be much faster than the carburizing method and did not introduce unknown variables into the steel.

Specimens of all plate thicknesses and in both as-rolled and normalized conditions were heated to temperatures ranging from 1,300° to 2,400° F, held 10 minutes, and gradient-quenched. There was no difference in grain size at any given temperature in the as-rolled and the normalized plates. Normalizing, therefore, apparently did not affect the grain size nor the grain-growth temperature.

Austenitic grain sizes of the ½-in. plates of some of the steels at various temperatures above the critical ranges of the steels are given in table 5. The grain-size designations are in accordance with those of the American Society for Testing Materials Specification E–19–39T.

TABLE 5.—*Austenitic grain size numbers of steels at various temperatures*

| Steel | Temperature, °F. | | | | Steel | Temperature, °F. | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1,600 | 1,700 | 1,800 | 1,900 | | 1,600 | 1,700 | 1,800 | 1,900 |
| 138 | 6 | 6 | 5 | 2 | 146 | 8 | 8 | 7, 8 | *3 and 7 |
| 139 | 7 | 7 | 7 | 7 | 147 | 8 | 8 | 8 | 2 |
| 140 | 6 | 5 | 2 | 1 | 148 | 6 | 5 | 4 | 3 |
| 141 | 8 | 7 | 7 | 7 | 149 | 7 | 7 | 7 | 7 |
| 144 | 8 | 8 | *4 and 6 | *3 and 6 | 150 | 7 | *5 and 7 | *3 and 7 | *2 and 7 |
| 145 | ------ | 6 | 5 | 3 | | | | | |

* Mixed.

[6] J. R. Vilella and E. C. Bain, *Revealing the austenitic grain size of steel*, Metal Progress **30**, 39 (1936).

Three steels, 139, 141, and 149, resisted grain growth up to 1,900° F and had fine grains at this temperature. In steels 146 and 147 there was grain growth at 1,900° F, in steels 138 and 144 at 1,800° F, while in steels 140, 145, 148, and 150 the grain size apparently started to increase at the top of the transformation range and continued increasing to the highest temperature. Steel 145 was not completely austenitic at 1,600° F; some procutectoid ferrite still existed at this temperature. Steels 144, 146, and 150 had mixed grain sizes, that is, while some grains showed growth at higher temperatures, some of the small grains did persist at those temperatures.

In general, the steels which had the highest coarsening temperature were those which did not contain appreciable amounts of carbide-forming elements. Those steels which coarsened at low temperatures, for the most part, did contain carbide-forming materials, particularly molybdenum. Three low-alloy steels, all of which contained molybdenum, and one plain carbon steel started to coarsen at the top of the critical range. One other molybdenum-containing steel did not coarsen at 1,900° F.

All of the steels which coarsened at low temperatures contained more than normal amounts of oxygen. Two of these steels, 145 and 148, contained abnormally high oxygen.

Most of the steels which coarsened at the highest temperatures contained copper and nickel in appreciable quantities. Two steels, 141 and 139, contained only small amounts of these elements.

McQuaid-Ehn grain-size tests were made in accordance with American Society for Testing Materials Specification E–19–39T. Specimens were packed in solid carburizer and heated at 1,700° F for 16 hours, then cooled in the furnace to 900° F to permit the rejection of cementite to the grain boundaries in the hypereutectoid zone.

Grain size numbers for the ½-in. plates are given in table 6. These include both the numbers after gradient-quenching and after carburizing for 16 hours at 1,700° F.

TABLE 6.—*Grain-size numbers at 1,700° F*

| Steel | After carburizing | After gradient-quenching | Steel | After carburizing | After gradient-quenching |
|---|---|---|---|---|---|
| 138 | 2 | 6 | 146 | 8 | 8 |
| 139 | 7 | 7 | 147 | 8 | 8 |
| 140 | 2 | 5 | 148 | 2 | 5 |
| 141 | 7 | 7 | 149 | 7 | 7 |
| 144 | 7 | 8 | 150 | 4 | *4 and 7 |
| 145 | 3 | 6 | | | |

*Mixed.

There was considerable difference in grain size after the two treatments. Those steels which after gradient-quenching had a small grain size generally had the same approximate size in the carburizing test. However, steels which had an intermediate size after quenching had larger size grains in the McQuaid-Ehn test. This is due most likely to the length of time at a given temperature and possibly to the introduction of carbon into the material during the test, thus changing some of the properties of the material.

In the ½-in. plates, steels 138, 140, 145, 148, and 150 had normal structures, steels 139 and 149 slightly abnormal, steels 141, 146, and 147 abnormal, and steel 144 very abnormal.

Comparing the two tests, it is found that, in general, the abnormal steels had the highest coarsening temperatures and those with normal structures had the lowest coarsening temperatures.

Chemical analyses and tensile-property tests indicated that not all sizes of plates from some steels were from the same heat. This was confirmed by the results of the carburizing tests. Steel 141, in the ¼-in. thickness, had a normal structure with large grains, while the ½- and ¾-in. plates had abnormal structures and small grains. Steel 149, likewise, had different grain sizes, the specimen from the ¼-in. plates having small grains and abnormal structures, while those from the ½- and ¾-in. plates had larger grains and normal structures. Steel 150 had a composite structure in the ¼-in. plate, in which the edge had large grains and normal structure while the interior was abnormal with small grains.

## III. METHOD OF TEST

### 1. GUIDED BEND TESTS

#### (a) PREPARATION OF SPECIMENS

Specimens from each thickness of plate, in both the as-rolled and the normalized conditions, were prepared as shown in figure 4. A 12- by 24-in. piece of the plate was cut with the short dimension parallel to the direction of rolling. A piece 4 by 24 in. of the same material was attached to this plate by means of double-fillet welds with the length of the welds perpendicular to the direction of rolling. The welds were continuous and made in one pass. One fillet was made and the specimen allowed to return to the original plate temperature before the second fillet was welded in the same direction as the first, that is, started from the same end.

All welds were made by the same operator, using direct current, reversed polarity, and organic-covered electrodes from the same source. Electrode sizes and current conditions for the three plate thickness were as follows:

| Plate thickness | Electrode size | Welding current | Arc voltage |
|---|---|---|---|
| *in.* | *in.* | *Amperes* | *Volts* |
| ¼ | ⅛ | 100 to 105 | 26 to 28 |
| ½ | 5/32 | 130 to 135 | 26 to 28 |
| ¾ | 3/16 | 160 to 170 | 26 to 28 |

Very close tolerances were maintained, and any specimens showing undercutting, improper weld size, or visible welding defects were discarded.

All the steels were welded when the plates were at room temperature. To simulate the conditions of welding in cold weather, additional plates were cooled to temperatures of 10°, 0°, −10°, and −20° F, and welding was started when the plates were at these temperatures.

Four specimens for the bend test and one specimen for examination of the microstructure and hardness tests were sawed from each assembly, as shown in figure 4. There was no further edge preparation nor were the welds machined in any manner.

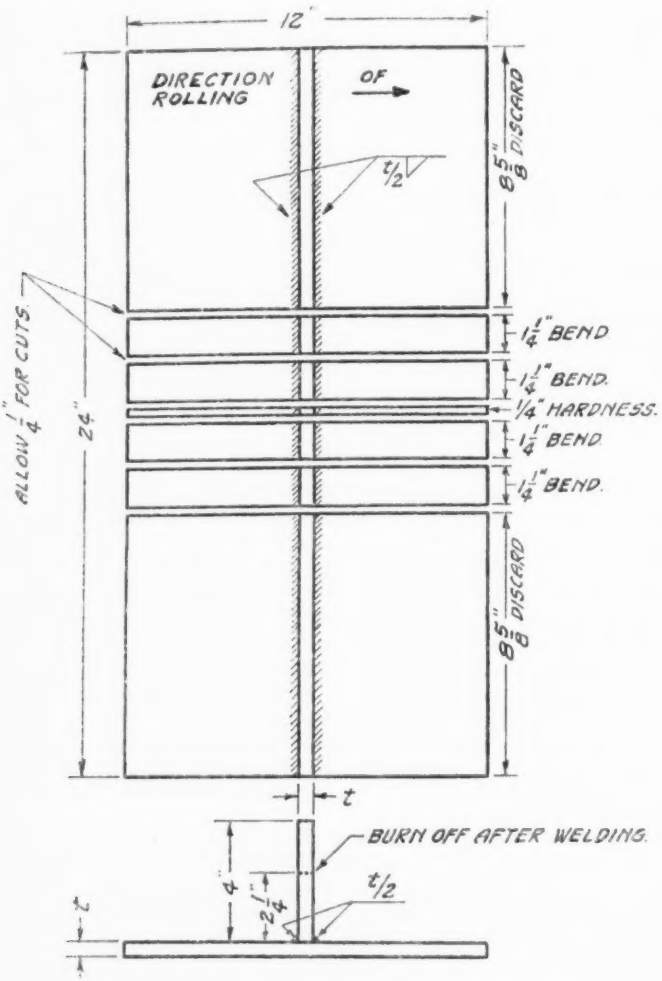



FIGURE 4.—*Plate layout and location of test specimens.*

(b) BENDING APPARATUS

A bending jig similar to that shown in figure 5 was designed for each thickness of plate. The specimen was supported on hardened steel cylinders, and the tongue of the T was wedged firmly in the guide, which moved freely in vertical ways. The specimen was loaded at the center on the face opposite to the T, through a plunger having a semicylindrical end of the same radius as the supporting cylinders. As the tongue of the specimen was constrained by the guide to move in a vertical plane, bending was forced to take place uniformly at the toe of each fillet. The deflection was measured on a scale attached to the plunger. The angle of bend (the supplement of the internal angle between the legs of the specimen) was obtained from a curve showing

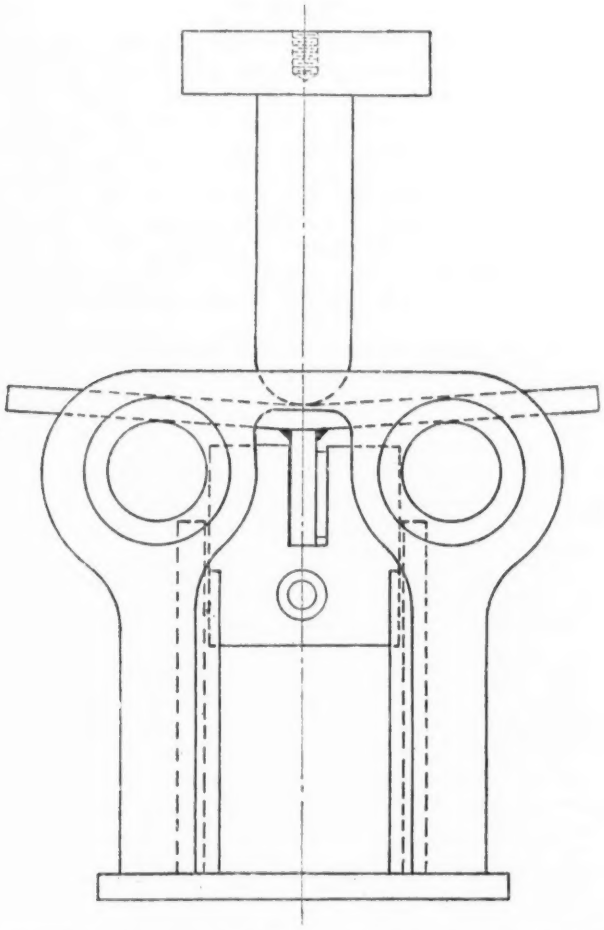


FIGURE 5.—*Diagram of bending jig, showing specimen in place.*

the relation between the deflection and the angle of bend. This curve was made by comparing measured angles of tested specimens with the deflections which produced these angles.

For each jig, the diameter of the supporting cylinders and of the end of the plunger was four times the nominal plate thickness, $t$, and the distance between centers of the supporting cylinders was $12t$. The jigs are shown in figure 6.

To observe the effects of low temperatures on the bending properties, bend tests were made at temperatures from $+10°$ F to $-20°$ F. For testing specimens at low temperatures, the jig was placed in an insulated tank containing a solution of ethylene glycol (50 percent by volume) in water. The liquid covered the specimen when in position in the jig and was cooled to the desired temperature by adding dry ice ($CO_2$).

(c) PROCEDURE

The jig was placed in a vertical screw-power, beam-and-poise testing machine. The specimen was laid across the cylindrical supports, as shown in figure 5, and a load of 100 lb. was applied through the plunger attached to the movable head of the testing machine. With this load seating the specimen firmly in the jig, the "zero deflection" of the scale attached to the plunger was read. The load was removed, and the tongue of the specimen was wedged in the slot of the guide.

The load was again applied to the specimen and increased continuously until the beam "dropped", indicating that the "maximum load" had been reached. The deflection of the specimen was the difference between the scale reading at this maximum load and the zero deflection.

If there was no visible crack when the beam dropped, loading was continued until the specimen cracked or the bending limit of the jig (about 120 degrees) was reached. If the specimen cracked either before or after maximum load, the deflection was read and the angle at initial failure was determined in the same manner as the angle at maximum load. The specimen was examined without removing the load, and if the failure was not complete, bending was continued to determine the direction of propagation of the failure and its extent at jig capacity.

In addition to deflections and loads, observations were made also of the kind or type of fracture, whether partial or complete, sudden or gradual, and of the location, whether in plate metal, bond zone, or weld metal.

For the tests at low temperatures, the same procedure was followed, except that the specimen could not be examined without removing it from the jig. The specimens were brought to the desired temperature before testing by placing them in the tank for at least 30 minutes prior to testing. Tests on the specimens with thermocouples in drilled holes showed that the temperature of the specimen rose only slightly during the time necessary to wedge the specimen into the guide.

The program called for the welding and testing of all sizes of steels at the following temperatures.

| Plate temperature before welding | Testing temperatures |
|---|---|
| °*F* | °*F* |
| 70 | 70, 10, 0, −10, −20 |
| 10 | 70 |
| 0 | 70, 10, 0, −10, −20 |
| −10 | 70 |
| −20 | 70, 10, 0, −10, −20 |

With four specimens to be tested under each condition, a total of 408 bend tests was required for the complete investigation of each steel. As the work continued, it was evident that some steels were unsatisfactory, and further tests were discontinued in order to shorten

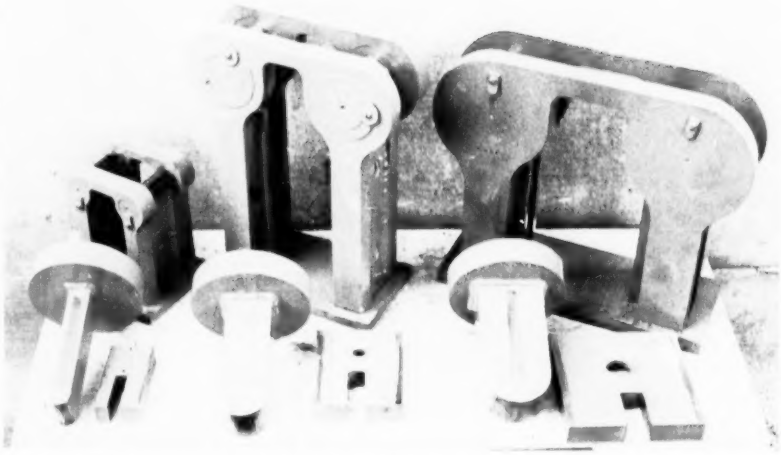
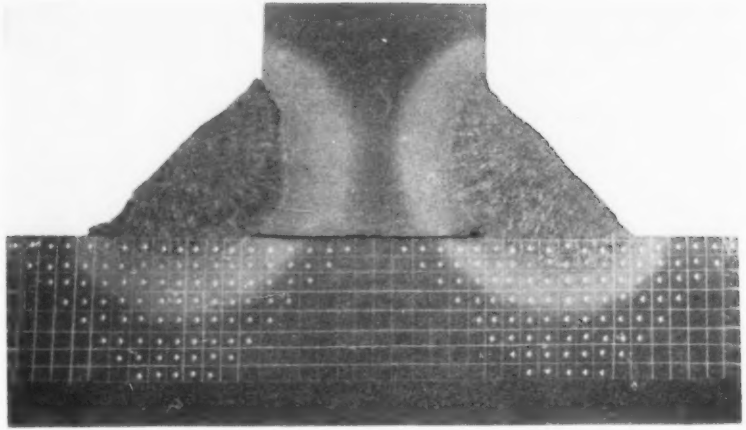


FIGURE 6. *Photograph of bending jigs used for* $\frac{1}{4}$*-,* $\frac{1}{2}$*-, and* $\frac{3}{4}$*-in. specimens, showing all essential parts of each jig.*



| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 144 | 142 | 141 | 144 | 144 | 148 | 148 | 142 | 143 | 141 | 158 | 162 | 193 | 180 | 172 | 171 | 159 | 153 | 153 |
| | 143 | 144 | 141 | 142 | 145 | 145 | 148 | 150 | 206 | 208 | 191 | 182 | 172 | 176 | 166 | 162 | 164 | |
| | | 141 | 158 | 142 | 146 | 146 | 170 | 173 | 171 | 159 | 157 | 168 | 170 | 165 | 161 | 157 | | |
| | | | 142 | 156 | 157 | 150 | 156 | 152 | 154 | 164 | 165 | 160 | 162 | 157 | 155 | | | |
| | | | | 153 | 157 | 159 | 141 | 152 | 152 | 154 | 158 | 158 | 156 | 154 | | | | |
| | | | | | 153 | 150 | 150 | 152 | 150 | 155 | 156 | 159 | 156 | | | | | |
| | | | | | | 154 | 159 | 151 | 150 | 150 | 150 | 150 | | | | | | |
| | | | | | | | 159 | 152 | 151 | 150 | 150 | | | | | | | |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 163 | 161 | 165 | 169 | 178 | 211 | 178 | 167 | 167 | 172 | 176 | 170 | 201 | 181 | 173 | 166 | 166 | 158 | 171 |
| | 165 | 163 | 168 | 171 | 165 | 192 | 208 | 191 | 199 | 219 | 204 | 188 | 174 | 174 | 164 | 157 | 148 | |
| | | 160 | 164 | 168 | 167 | 170 | 174 | 178 | 178 | 179 | 171 | 176 | 170 | 166 | 165 | 165 | | |
| | | | 164 | 163 | 164 | 164 | 167 | 168 | 168 | 172 | 169 | 165 | 160 | 157 | 150 | | | |
| | | | | 162 | 160 | 168 | 166 | 165 | 165 | 167 | 164 | 163 | 162 | 156 | | | | |
| | | | | | 163 | 156 | 163 | 161 | 165 | 164 | 160 | 163 | 161 | | | | | |
| | | | | | | 163 | 161 | 163 | 164 | 167 | 165 | 163 | | | | | | |
| | | | | | | | 167 | 162 | 164 | 161 | 158 | | | | | | | |

FIGURE 7.—*Location of Vickers indentations on specimens and hardness numbers corresponding to the indentations.*

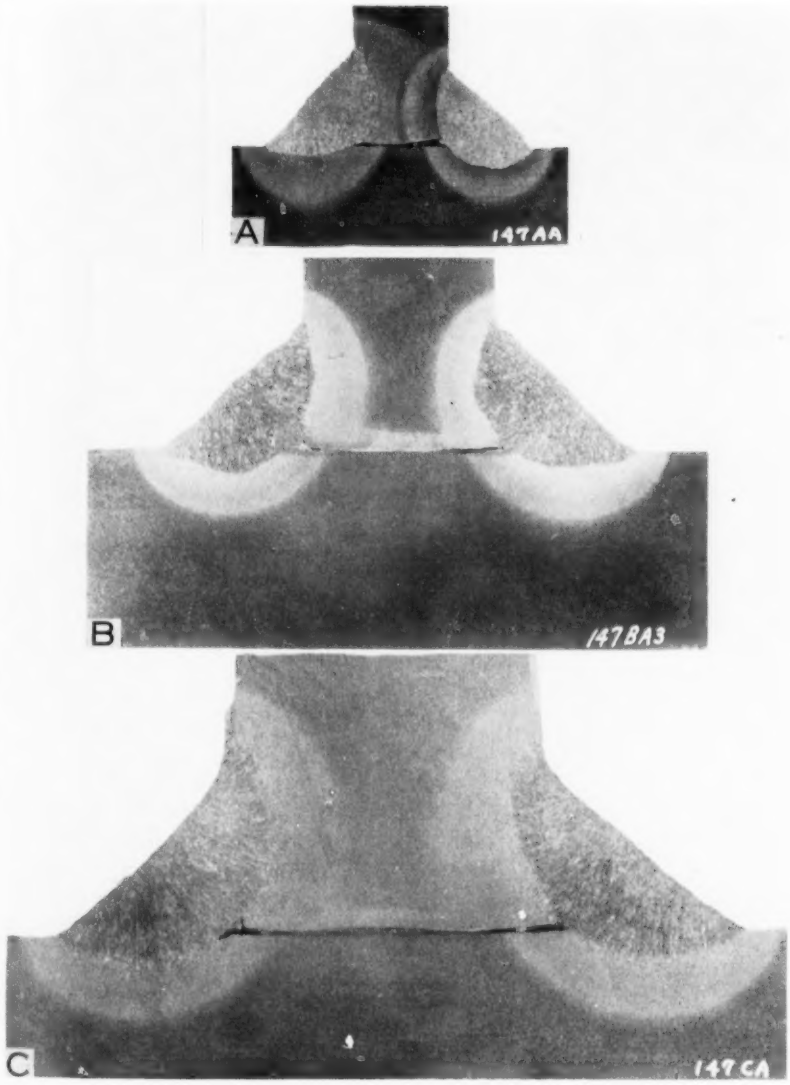



FIGURE 8.—*Typical macrostructures of the welded specimens.*

*A*, ¼-in. plate; *B*, ½-in. plate; *C*, ¾-in. plate.

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the program. The complete program of tests was carried out on only 6 of the 18 steels (Nos. 139, 144, 146, 147, 149, and 150).

## 2. HARDNESS TESTS

One specimen for each composition, thickness, and condition of steel was ruled in millimeters, as shown in figure 7, and Vickers numbers were obtained for each square in the heat-affected zone.

Results for the six completely tested steels are given in table 7, showing the hardness of the plate metal before and after welding.

TABLE 7.—*Effect of welding on hardness of plate metals*

| Steel | Plate thickness | Original plate | | After welding highest value | | Increase of hardness | |
|---|---|---|---|---|---|---|---|
| | | As-rolled | Normalized | As-rolled | Normalized | As-rolled | Normalized |
| | *In.* | *Vickers No.* | *Vickers No.* | *Vickers No.* | *Vickers No.* | *Vickers No.* | *Vickers No.* |
| 139 | 1/4 | 153 | 145 | 215 | 194 | 62 | 49 |
| | 1/2 | 149 | 144 | 219 | 214 | 70 | 70 |
| | 3/4 | 149 | 146 | 194 | 192 | 45 | 47 |
| 144 | 1/4 | 177 | 154 | 247 | 230 | 70 | 76 |
| | 1/2 | 150 | 159 | 252 | 231 | 102 | 72 |
| | 3/4 | 182 | 152 | 242 | 227 | 60 | 75 |
| 146 | 1/4 | 156 | 155 | 185 | 190 | 29 | 35 |
| | 1/2 | 150 | 150 | 198 | 200 | 48 | 50 |
| | 3/4 | 154 | 149 | 206 | 200 | 52 | 51 |
| 147 | 1/4 | 164 | 164 | 251 | 240 | 87 | 76 |
| | 1/2 | 164 | 158 | 238 | 271 | 74 | 113 |
| | 3/4 | 171 | 157 | 223 | 214 | 52 | 57 |
| 149 | 1/4 | 165 | 160 | 208 | 198 | 43 | 38 |
| | 1/2 | 158 | 156 | 195 | 193 | 37 | 37 |
| | 3/4 | 153 | 152 | 197 | 188 | 44 | 36 |
| 150 | 1/4 | 168 | 158 | 224 | 223 | 56 | 65 |
| | 1/2 | 152 | 150 | 209 | 229 | 57 | 79 |
| | 3/4 | 155 | 157 | 208 | 225 | 53 | 68 |

The highest hardness (182) of the as-rolled plates was found in the ¾-in. plate of steel 144 and the lowest (149) in the ½- and ¾-in. plates of steel 139. The ½-in. plate of steel 144 also had a low value (150). After welding, the highest hardness was found in the ½-in. plate of steel 144 (252), an increase of 102 Vickers numbers.

The highest hardness of the normalized plates (164) was found in the ¼-in. plate of steel 147. The hardest point after welding was 271, found in the ½-in. plate of steel 147. This plate also had the greatest increase in Vickers numbers (113) as a result of welding.

None of the specimens hardened excessively, and the ranges of hardness were comparatively narrow.

## 3. MACROSTRUCTURES

Specimens from the six completely tested steels were polished, etched, and examined both macroscopically and microscopically. A typical macrophotograph is shown in figure 8. The results of these studies showed that all welds were of proper contour and size, that heat penetration was normal for the plate and electrode size used, and that there were no serious defects in the plate or weld metals.

Microstructures of welded specimens showed that, with the exception of steel 147, the grains at the fusion boundary were not excessively large. There were no sharp boundary lines, and the plate metals for the most part diffused gradually into weld metals. Likewise the changes in structure in the transition zones of the plate metals were very gradual.

## IV. RESULTS

### 1. MAXIMUM LOAD

For the specimens in which no fracture occurred the load increased, with increase in angle of bend, to a maximum and then decreased continuously without any increase, until the limit of the jig was reached. Usually the maximum load occurred after the specimen had bent 60°. The agreement between duplicate specimens, as to both maximum load and angle, was generally very close.

Specimens from some of the steels cracked audibly or visibly while the load was still increasing and at bend angles usually much less than 60°. In such cases the results of duplicate specimens did not agree, either in load or angle at which cracking occurred. For specimens from other steels, cracking did not occur until after the maximum load had been attained and the load was decreasing. When this occurred, there also was lack of agreement among duplicate specimens for the load at which cracking occurred, although the agreement on maximum load and angle at maximum load was close.

Because the maximum load on a specimen was affected directly by changes in dimensions that were indeterminate on these specimens and could not be reduced to stress values, this maximum load in the bend test was not considered an important basis of comparison. It was even more difficult to determine exactly the load, and particularly the angle at which cracking began, and no attempt was made to use these as a basis of comparison. The maximum load, with or without failure by cracking, was indicated by a drop of the beam of the testing machine similar to that at the maximum load in a tensile test of a ductile metal. The angle of bend at this load was readily determined, and also whether the failure occurred before or after the maximum load had been passed. All failures were in one or the other category, and those which appeared to coincide with the maximum load were considered to have occurred under an increasing load.

Although it would not be advisable to recommend minimum numerical values for maximum load and angle of bend, alone, as a basis for acceptable welding quality, it was considered that the higher these values the greater were the indicated strength and ductility of the joint. These values were considered useful for comparisons of specimens of different steels welded and tested under the same conditions. The use of values for angle of bend at maximum load is discussed in the following section.

The average values of maximum loads are given in table 8. In this and other tables where data are incomplete, the value is followed by a small "x." Since the maximum load is apparently not a simple function of plate thickness, the values for the various plate sizes cannot be directly compared; but the rank numbers, which are based

Table 8 . - MAXIMUM LOADS

| Steel No. & Cond. | Test Temp. °F | 1/4" Weld Temperature, °F 70 | 10 | 0 | -10 | -20 | Rank | 1/2" Weld Temperature, °F 70 | 10 | 0 | -10 | - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 139 AR | 70 | 3755 | 3560 | 3460 | 3780 | 3770 | 1 | 5810 | 6050 | 5850 | 5620 | 5 |
| | 10 | 3960 | | 3710 | | 3960 | | 6540 | | 6610 | | 6 |
| | 0 | 3960 | | 3850 | | 3990 | | 6800 | | 6620 | | 6 |
| | -10 | 4050 | | 3880 | | 3990 | | 6500 | | 6690 | | 6 |
| | -20 | 4030 | | 3780 | | 4070 | | 7040 | | 6900 | | 6 |
| | Ave. | All Temperatures | | | | 3860 | 2 | | | | | 6 |
| 139 N | 70 | 3687 | 3620 | 3700 | 3660 | 3700 | 1 | 6162 | 5550 | 5120 | 4840 | 4 |
| | 10 | 3840 | | 3740 | | 3910 | | 6860 | | 6850 | | 7 |
| | 0 | 3870 | | 3900 | | 4000 | | 6860 | | 6920 | | 6 |
| | -10 | 3980 | | 3960 | | 3960 | | 7010 | | 6700 | | 6 |
| | -20 | 3980 | | 3940 | | 3910 | | 7040 | | 6780 | | 6 |
| | Ave. | All Temperatures | | | | 3840 | 2 | | | | | 6 |
| 144 AR | 70 | 5100 | 5420 | 5350 | 5180 | 5000 | 8 | 7570 | 7748 | 7675 | 8055 | 7 |
| | 10 | 5490 | | 5620 | | 5260 | | 8181 | | 8344 | | 8 |
| | 0 | 5590 | | 5490 | | 5350 | | 8355 | | 8484 | | 8 |
| | -10 | 5780 | | 5360 | | 5250 | | 8320 | | 8221 | | 8 |
| | -20 | 5740 | | 5280 | | 5570 | | 8316 | | 8566 | | 8 |
| | Ave. | All Temperatures | | | | 5400 | 10 | | | | | 8 |
| 144 N | 70 | 4685 | 4450 | 4900 | 4630 | 4590 | 6 | 7655 | 7220 | 7362 | 7615 | 7 |
| | 10 | 4700 | | 4600 | | 4730 | | 7845 | | 7870 | | 7 |
| | 0 | 4460 | | 4790 | | 4880 | | 7786 | | 7595 | | 7 |
| | -10 | 4660 | | 4680 | | 4470 | | 7860 | | 7870 | | 7 |
| | -20 | 4700 | | 4750 | | 4760 | | 8108 | | 7940 | | 7 |
| | Ave. | All Temperatures | | | | 4670 | 6 | | | | | 7 |
| 146 AR | 70 | 3968 | -- | 4010 | 4120 | 4160 | 2 | 6962 | 6925 | 6888 | 6988 | 7 |
| | 10 | 4170 | | 4335 | | 4160 | | 7670 | | 7500 | | 7 |
| | 0 | 4340 | | 4380 | | 4260 | | 7638 | | 7425 | | 7 |
| | -10 | 4315 | | 4170 | | 4050 | | 7775 | | 7588 | | 7 |
| | -20 | 4280 | | 4300 | | 4290 | | 7838 | | 7733 | | 7 |
| | Ave. | All Temperatures | | | | 4210 | 4 | | | | | 7 |
| 146 N | 70 | 3603 | 3730 | 3590 | 3760 | 3600 | 0 | 6825 | 6838 | 6912 | 6912 | 6 |
| | 10 | 3980 | | 3950 | | 3630 | | 7425 | | 7160 | | 7 |
| | 0 | 3828 | | 3770 | | 3950 | | 7475 | | 7288 | | 7 |
| | -10 | 4050 | | 3900 | | 3930 | | 7462 | | 7062 | | 7 |
| | -20 | 4140 | | 4060 | | 3810 | | 7562 | | 7500 | | 7 |
| | Ave. | All Temperatures | | | | 3840 | 2 | | | | | 7 |
| 147 AR. | 70 | 4051 | 4220 | 4325 | 4320 | 4530 | 3 | 7150 | 7188 | 7213 | 7460 | 7 |
| | 10 | 4390 | | 4460 | | 4500 | | 8038 | | 7850 | | 7 |
| | 0 | 4350 | | 4475 | | 4525 | | 8062 | | 7850 | | 7 |
| | -10 | 4360 | | 4690 | | 4500 | | 8488 | | 8200 | | 7 |
| | -20 | 4570 | | 4600 | | 4475 | | 8250 | | 7950 | | 7 |
| | Ave. | All Temperatures | | | | 4430 | 5 | | | | | 7 |
| 147 N | 70 | 3808 | 3870 | 3862 | 3958 | 4068 | 2 | 7288 | 7100 | 7000 | 7350 | 7 |
| | 10 | 4118 | | 3692 | | 4255 | | 7612 | | 7750 | | 7 |
| | 0 | 4098 | | 4222 | | 4185 | | 7662 | | 7650 | | 7 |
| | -10 | 4095 | | 4135 | | 4100 | | 7725 | | 7825 | | 7 |
| | -20 | 4262 | | 4218 | | 4245 | | 7588 | | 7762 | | 7 |
| | Ave. | All Temperatures | | | | 4070 | 3 | | | | | 7 |
| 149 AR | 70 | 4745 | 4766 | 4542 | 4397 | 4486 | 6 | 7062 | 7594 | 7095 | 7591 | 7 |
| | 10 | 5040 | | 4710 | | 4400 | | 7264 | | 7729 | | 7 |
| | 0 | -- | | 4570 | | 4340 | | 7462 | | 7671 | | 7 |
| | -10 | -- | | 4580 | | 4520 | | 7371 | | 7408 | | 7 |
| | -20 | -- | | 4840 | | 4660 | | 7550 | | 7505 | | 7 |
| | Ave. | All Temperatures | | | | 4620x | 6 | | | | | 7 |
| 149 N | 70 | 4360 | 4710 | 4670 | 4508 | 4585 | 4 | 6750 | 6895 | 6939 | 7270 | 7 |
| | 10 | -- | | 4890 | | 4670 | | 7081 | | 7295 | | 7 |
| | 0 | -- | | 4820 | | 4390 | | 7144 | | 7266 | | 7 |
| | -10 | -- | | 4630 | | 4550 | | 7291 | | 7382 | | 7 |
| | -20 | -- | | 4760 | | 4370 | | 7236 | | 7385 | | 7 |
| | Ave. | All Temperatures | | | | 4610x | 6 | | | | | 7 |
| 150 AR | 70 | 4345 | 4510 | 4270 | 4530 | 4510 | 4 | 7850 | 7458 | 7677 | 7632 | 7 |
| | 10 | 4710 | | 4090 | | 4980 | | 8184 | | 8230 | | 8 |
| | 0 | 4440 | | 4750 | | 4720 | | 8021 | | 8134 | | 8 |
| | -10 | 4390 | | 4740 | | 4550 | | 8004 | | 7906 | | 8 |
| | -20 | 4450 | | 4720 | | 4610 | | 7896 | | 7784 | | 8 |
| | Ave. | All Temperatures | | | | 4550 | 5 | | | | | 7 |
| 150 N | 70 | 3860 | 3680 | 3650 | 3670 | 3242 | 2 | 7112 | 6768 | 6855 | 6812 | 7 |
| | 10 | 4170 | | 4060 | | 4180 | | 7474 | | 7466 | | 7 |
| | 0 | 4300 | | 4120 | | 3680 | | 7502 | | 7540 | | 7 |
| | -10 | 3740 | | 3880 | | 3700 | | 7514 | | 7522 | | 7 |
| | -20 | 3701 | | 3770 | | 3830 | | 7495 | | 7469 | | 7 |
| | Ave. | All Temperatures | | | | 3840 | 2 | | | | | 7 |

Determination of Ra

| Range | | | | | | |
|---|---|---|---|---|---|---|
| Subdivisions | 1/4" | Under 3609 | 3610-3799 | 3800-3999 | 4000-4199 | 4200-43 |
| | 1/2" | Under 5999 | 6000-6299 | 6300-6599 | 6600-6899 | 6900-71 |
| | 3/4" | Under 8999 | 9000-9199 | 9200-9399 | 9400-9599 | 9600-97 |
| Rank Numbers | | 0 | 1 | 2 | 3 | 4 |

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UM LOADS. (Average of 4 Specimens.)

| 1/2" | | | 3/4" | | | | | | All Sizes Combined | | Steel No. & Cond. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ture, °F | | Rank | Weld Temperature, °F | | | | | Rank | 70°F | All Temp. | |
| -10 | -20 | | 70 | 10 | 0 | -10 | -20 | | Ave. Rank | Ave. Rank | |
| 5620 | 5600 | 0 | 9450 | 9390 | 9160 | 9160 | 9250 | 3 | 1.3 | | 139 AR |
| | 6840 | | 10200 | | 10290 | | 9960 | | | | |
| | 6790 | | 10220 | | 10260 | | 9800 | | | | |
| | 6410 | | 10410 | | 10080 | | 10040 | | | | |
| | 6580 | | 10140 | | 10180 | | 9940 | | | | |
| | 6430 | 2 | | | | | 9680 | 5 | | 3.0 | |
| 4840 | 4700 | 1 | 9088 | 9070 | 9440 | 9280 | 8950 | 1 | 1.0 | | 139 M |
| | 7120 | | 9640 | | 9610 | | 9740 | | | | |
| | 6950 | | 9540 | | 9910 | | 9900 | | | | |
| | 6880 | | 9760 | | 9550 | | 9750 | | | | |
| | 6890 | | 9890 | | 9600 | | 10100 | | | | |
| | 6430 | 2 | | | | | 9580 | 3 | | 2.3 | |
| 8055 | 7820 | 6 | 10210 | 10300 | 10380 | 10580 | 10475 | 7 | 7.0 | | 144 AR |
| | 8049 | | 10780 | | 10800 | | 10820 | | | | |
| | 8005 | | 10510 | | 10800 | | 10700 | | | | |
| | 8141 | | 10720 | | 10830 | | 10960 | | | | |
| | 8251 | | 10680 | | 10670 | | 10950 | | | | |
| | 8120 | 8 | | | | | 10660 | 9 | | 9.0 | |
| 7615 | 7145 | 6 | 8962 | 8900 | 8800 | 9020 | 9125 | 0 | 4.0 | | 144 M |
| | 7929 | | 9420 | | 9400 | | 9130 | | | | |
| | 7738 | | 9260 | | 9140 | | 9175 | | | | |
| | 7640 | | 9360 | | 9080 | | 9410 | | | | |
| | 7716 | | 9626 | | 9382 | | 9808 | | | | |
| | 7700 | 6 | | | | | 9230 | 2 | | 4.7 | |
| 6988 | 7038 | 4 | 10300 | 10000 | 9950 | 10140 | 10160 | 7 | 4.3 | | 146 AR |
| | 7388 | | 11000 | | 10760 | | 10690 | | | | |
| | 7488 | | 11290 | | 11390 | | 10575 | | | | |
| | 7525 | | 10790 | | 10750 | | 10925 | | | | |
| | 7562 | | 11250 | | 11150 | | 10690 | | | | |
| | 7410 | 5 | | | | | 10690 | 9 | | 6.0 | |
| 6912 | 6925 | 3 | 9738 | 9890 | 9800 | 9890 | 9850 | 4 | 2.3 | | 146 M |
| | 7500 | | 10390 | | 10420 | | 10500 | | | | |
| | 7425 | | 10600 | | 10740 | | 10490 | | | | |
| | 7475 | | 10300 | | 10500 | | 10580 | | | | |
| | 7581 | | 10320 | | 10560 | | 10690 | | | | |
| | 7250 | 5 | | | | | 10310 | 7 | | 4.7 | |
| 7460 | 7512 | 4 | 10600 | 10450 | 10910 | 10660 | 10860 | 9 | 5.3 | | 147 AR |
| | 7788 | | 11450 | | 11120 | | 11090 | | | | |
| | 7838 | | 11550 | | 11250 | | 11490 | | | | |
| | 7650 | | 11600 | | 10425 | | 11550 | | | | |
| | 7975 | | 11990 | | 11260 | | 11275 | | | | |
| | 7790 | 6 | | | | | 11150 | 10 | | 7.0 | |
| 7350 | 7392 | 5 | 10050 | 9950 | 8960 | 10250 | 10210 | 6 | 4.3 | | 147 M |
| | 7688 | | 11100 | | 10710 | | 10910 | | | | |
| | 7750 | | 11140 | | 10775 | | 10930 | | | | |
| | 7675 | | 10940 | | 11050 | | 11025 | | | | |
| | 7688 | | 11580 | | 11040 | | 10900 | | | | |
| | 7560 | 6 | | | | | 10680 | 9 | | 6.0 | |
| 7591 | 7222 | 4 | 10100 | 10370 | 10385 | 10370 | 10440 | 6 | 5.3 | | 149 AR |
| | 7638 | | 10475 | | 10705 | | 10490 | | | | |
| | 7744 | | 10270 | | 10410 | | 10205 | | | | |
| | 7496 | | 10420 | | 10460 | | 10230 | | | | |
| | 7728 | | 10340 | | 10930 | | 10550 | | | | |
| | 7490 | 5 | | | | | 10420 | 8 | | 6.3 | |
| 7270 | 7195 | 3 | 10050 | 10250 | 10140 | 9840 | 10060 | 6 | 4.3 | | 149 M |
| | 7701 | | 10250 | | 10740 | | 10170 | | | | |
| | 7641 | | 10060 | | 10390 | | 10310 | | | | |
| | 7450 | | 10100 | | 10128 | | 10230 | | | | |
| | 7462 | | 10320 | | 10320 | | 10440 | | | | |
| | 7260 | 5 | | | | | 10230 | 7 | | 6.0 | |
| 7632 | 7542 | 7 | 8975 | 9640 | 9500 | 9390 | 9320 | 0 | 3.7 | | 150 AR |
| | 8344 | | 9490 | | 9360 | | 9700 | | | | |
| | 8284 | | 9350 | | 9630 | | 9540 | | | | |
| | 8166 | | 9370 | | 9450 | | 9650 | | | | |
| | 8106 | | 9860 | | 9480 | | 9840 | | | | |
| | 7950 | 7 | | | | | 9500 | 3 | | 5.0 | |
| 6812 | 7052 | 4 | 8962 | 9150 | 9250 | 9040 | 8800 | 0 | 2.0 | | 150 M |
| | 7015 | | 9270 | | 9140 | | 9070 | | | | |
| | 7725 | | 9080 | | 9090 | | 9172 | | | | |
| | 7630 | | 9210 | | 9290 | | 9330 | | | | |
| | 7076 | | 9420 | | 9140 | | 9510 | | | | |
| | 7300 | 5 | | | | | 9170 | 1 | | 2.7 | |

ion of Rank

| | | | | | | |
|---|---|---|---|---|---|---|
| 4200-4399 | 4400-4599 | 4600-4799 | 4800-4999 | 5000-5199 | 5200-5399 | 5400 & over |
| 6900-7199 | 7200-7499 | 7500-7799 | 7800-8099 | 8100-8399 | 8400-8699 | 8700 & over |
| 9600-9799 | 9800-9999 | 10000-10199 | 10200-10399 | 10400-10599 | 10600-10799 | 10800 & over |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |

Table 9. - ANGLES OF BE

| Plate Size | | 1/4" | | | | | | 1/2" | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Steel No. & Cond. | Test Temp °F | Weld Temperature, °F 70° | 10° | 0° | -10° | -20° | Rank | Weld Temperature, °F 70° | 10° | 0° | -10° | -20° | Rank |
| 139 AR | 70 | -- | 47x | 56x | 64x | 59x | - | 70x | 56x | 57x | 59x | 63x | 9 |
| | 10 | 66 | | 54 | | 61 | | 56 | | 52 | | 66 | |
| | 0 | 63 | | 65 | | 58 | | 57 | | 55 | | 64 | |
| | -10 | 65 | | 61 | | 57 | | 43 | | 50 | | 51 | |
| | -20 | 60 | | 51 | | 55 | | 55 | | 56 | | 45 | |
| | Ave. | All Temperatures | | | | 59x | 4 | | | | | 56x | 2 |
| 139 N | 70 | 65 | 67 | 66 | 65 | 67 | 7 | 68 | 71x | 67x | 70x | 62x | 8 |
| | 10 | 66 | | 60 | | 65 | | 64 | | 69 | | 63 | |
| | 0 | 64 | | 63 | | 66 | | 63 | | 67 | | 63 | |
| | -10 | 66 | | 65 | | 66 | | 67 | | 52 | | 70 | |
| | -20 | 68 | | 66 | | 70 | | 57 | | 62 | | 63 | |
| | Ave. | All Temperatures | | | | 66 | 7 | | | | | 65x | 7 |
| 144 AR | 70 | 61 | 53 | 47 | 58 | 54 | 5 | 56 | 54 | 56 | 60 | 57 | 2 |
| | 10 | 49 | | 48 | | 52 | | 56 | | 61 | | 62 | |
| | 0 | 52 | | 46 | | 47 | | 63 | | 63 | | 62 | |
| | -10 | 53 | | 52 | | 55 | | 61 | | 59 | | 63 | |
| | -20 | 52 | | 51 | | 50 | | 60 | | 69 | | 62 | |
| | Ave. | All Temperatures | | | | 52 | 0 | | | | | 60 | 4 |
| 144 N | 70 | 72 | 66 | 66 | 65 | 63 | 10 | 68 | 60 | 66 | 67 | 64 | 8 |
| | 10 | 61 | | 62 | | 57 | | 64 | | 65 | | 67 | |
| | 0 | 62 | | 59 | | 51 | | 67 | | 66 | | 63 | |
| | -10 | 61 | | 59 | | 53 | | 67 | | 64 | | 70 | |
| | -20 | 56 | | 65 | | 62 | | 71 | | 67 | | 62 | |
| | Ave. | All Temperatures | | | | 61 | 5 | | | | | 66 | 7 |
| 146 AR | 70 | 65 | -- | 66 | 65 | 65 | 7 | 75 | 67 | 67 | 69 | 69 | 10 |
| | 10 | 65 | | 70 | | 63 | | 68 | | 68 | | 67 | |
| | 0 | 65 | | 69 | | 63 | | 74 | | 61 | | 64 | |
| | -10 | 64 | | 59 | | 63 | | 73 | | 69 | | 65 | |
| | -20 | 66 | | 63 | | 64 | | 72 | | 70 | | 63 | |
| | Ave. | All Temperatures | | | | 65 | 7 | | | | | 68 | 8 |
| 146 N | 70 | 61 | 67 | 65 | 66 | 66 | 5 | 67 | 69 | 68 | 69 | 68 | 8 |
| | 10 | 68 | | 70 | | 61 | | 72 | | 69 | | 70 | |
| | 0 | 67 | | 68 | | 65 | | 70 | | 70 | | 67 | |
| | -10 | 66 | | 64 | | 68 | | 71 | | 53 | | 72 | |
| | -20 | 69 | | 66 | | 72 | | 61 | | 67 | | 70 | |
| | Ave, | All Temperatures | | | | 66 | 7 | | | | | 68 | 8 |
| 147 AR | 70 | 60 | 63 | 61 | 60 | 64 | 4 | 73 | 56 | 58 | 62 | 59 | 10 |
| | 10 | 64 | | 60 | | 60 | | 68 | | 65 | | 65 | |
| | 0 | 62 | | 61 | | 61 | | 69 | | 67 | | 69 | |
| | -10 | 60 | | 62 | | 63 | | 64 | | 60 | | 56 | |
| | -20 | 61 | | 64 | | 64 | | 69 | | 65 | | 57 | |
| | Ave. | All Temperatures | | | | 62 | 5 | | | | | 64 | 6 |
| 147 N | 70 | 62 | 64 | 64 | 64 | 65 | 5 | 69 | 67 | 62 | 64 | 66 | 9 |
| | 10 | 63 | | 58 | | 63 | | 69 | | 72 | | 68 | |
| | 0 | 68 | | 64 | | 62 | | 69 | | 65 | | 70 | |
| | -10 | 69 | | 65 | | 64 | | 70 | | 71 | | 71 | |
| | -20 | 64 | | 65 | | 66 | | 56 | | 75 | | 67 | |
| | Ave. | All Temperatures | | | | 64 | 6 | | | | | 68 | 8 |
| 149 AR | 70 | 60 | 75 | 58 | 57 | 58 | 4 | 69 | 62 | 64 | 63 | 62 | 9 |
| | 10 | 60 | | 60 | | 48 | | 66 | | 57 | | 58 | |
| | 0 | -- | | 60 | | 59 | | 66 | | 66 | | 70 | |
| | -10 | -- | | 60 | | 61 | | 70 | | 59 | | 51 | |
| | -20 | -- | | 56 | | 58 | | 71 | | 56 | | 61 | |
| | Ave. | All Temperatures | | | | 59x | 4 | | | | | 63 | 6 |
| 149 N | 70 | 68 | 63 | 65 | 61 | 64 | 8 | 69 | 65 | 63 | 63 | 63 | 9 |
| | 10 | -- | | 65 | | 60 | | 69 | | 66 | | 59 | |
| | 0 | -- | | 62 | | 52 | | 63 | | 65 | | 64 | |
| | -10 | -- | | 52 | | 60 | | 68 | | 64 | | 56 | |
| | -20 | -- | | 46 | | 41 | | 71 | | 58 | | 59 | |
| | Ave. | All Temperatures | | | | 58x | 3 | | | | | 64 | 6 |
| 150 AR | 70 | 60 | 55 | 50 | 54 | 60 | 4 | 68 | 59 | 63 | 56 | 53 | 8 |
| | 10 | 59 | | 40 | | 67 | | 67 | | 70 | | 69 | |
| | 0 | 54 | | 66 | | 62 | | 61 | | 68 | | 62 | |
| | -10 | 55 | | 58 | | 57 | | 64 | | 59 | | 63 | |
| | -20 | 53 | | 57 | | 56 | | 57 | | 59 | | 60 | |
| | Ave. | All Temperatures | | | | 57 | 3 | | | | | 62 | 5 |
| 150 N | 70 | 69 | 54 | 56 | 60 | 49 | 9 | 68 | 61 | 63 | 62 | 63 | 8 |
| | 10 | 70 | | 72 | | 69 | | 66 | | 72 | | 48 | |
| | 0 | 68 | | 67 | | 59 | | 71 | | 72 | | 64 | |
| | -10 | 67 | | 59 | | 60 | | 69 | | 69 | | 70 | |
| | -20 | 60 | | 55 | | 62 | | 62 | | 66 | | 42 | |
| | Ave. | All Temperatures | | | | 62 | 5 | | | | | 64 | 6 |

Determination of

| Range Subdivisions | Under 52.9 | 53-54.9 | 55-56.9 | 57-58.9 | 59-60.9 | 61-6 |
|---|---|---|---|---|---|---|
| Rank Numbers | 0 | 1 | 2 | 3 | 4 | |

ES OF BEND AT MAXIMUM LOAD.

| °F -20° | Rank | 3/4" Weld Temperature, °F 70° | 10° | 0° | -10° | -20° | Rank | All Sizes Combined W & T at 70°F Ave. | Rank | W & T All Temp. Ave. | Rank | Size Steel No. & Cond. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 63x 66 64 51 45 56x | 9 2 | 68 65 63 66 60 | 66x | 65x 62 66 52 60 | 64x | 67x 60 61 66 63 63x | 8 6 | 69.0x | 9 | 59.3x | 4 | 139 AR |
| 62x 63 63 70 63 65x | 8 7 | 66 62 67 67 63 | 66 | 64 64 63 56 54 | 62 | 65 64 66 54 64 63 | 7 6 | 66.3 | 7 | 64.7x | 6 | 139 N |
| 57 62 62 63 62 60 | 2 4 | 51 57 58 55 60 | 50 | 48 60 56 57 48 | 48 | 51 59 58 56 54 54 | 0 1 | 56.0 | 2 | 55.3 | 2 | 144 AR |
| 64 67 63 70 62 66 | 8 7 | 64 63 62 56 68 | 58 | 58 64 59 58 64 | 60 | 64 65 64 60 58 61 | 6 5 | 68.0 | 8 | 62.7 | 5 | 144 N |
| 69 67 64 65 63 68 | 10 8 | 62 65 64 66 62 | 65 | 64 64 63 68 63 | 66 | 63 65 64 63 67 64 | 5 6 | 67.3 | 8 | 65.7 | 7 | 146 AR |
| 68 70 67 72 70 68 | 8 8 | 66 64 64 60 59 | 65 | 65 62 66 64 64 | 63 | 64 62x 66 64 68 64 | 7 6 | 64.7 | 6 | 66.0 | 7 | 146 N |
| 59 65 69 56 57 64 | 10 6 | 63 59 65 62 62 | 59 | 62 64 63 54 54 | 62 | 61 62 63 55 49 60 | 6 4 | 65.3 | 7 | 62.0 | 5 | 147 AR |
| 66 68 70 71 67 68 | 9 8 | 63 59 61 63 57 | 63 | 64 65 59 62 66 | 66 | 62 66 62 64 58 62 | 6 5 | 64.7 | 6 | 64.7 | 6 | 147 N |
| 62 58 70 51 61 63 | 9 6 | 67 62 58 60 52 | 66 | 60 62 62 59 56 | 65 | 65 54 51 55 55 59 | 8 4 | 65.3 | 7 | 60.3 | 4 | 149 AR |
| 63 59 64 56 59 64 | 9 6 | 66 67 60 59 57 | 66 | 60 62 61 58 54 | 61 | 64 53 60 52 57 60 | 7 4 | 67.7 | 8 | 60.7 | 4 | 149 N |
| 53 69 62 63 60 62 | 8 5 | 50 61 61 51 49 | 64 | 66 55 54 60 54 | 66 | 63 62 61 56 58 58 | 0 3 | 59.3 | 4 | 59.0 | 4 | 150 AR |
| 63 48 64 70 42 64 | 8 6 | 66 67 62 60 56 | 64 | 64 62 61 58 62 | 64 | 68 61 59 57 64 62 | 7 5 | 67.7 | 8 | 62.7 | 5 | 150 N |

ation of Rank

| 9 | 61- 62.9 | 63- 64.9 | 65- 66.9 | 67- 68.9 | 69- 70.9 | 71- & over | Range Subdivisions |
|---|---|---|---|---|---|---|---|
| | 5 | 6 | 7 | 8 | 9 | 10 | Rank Numbers |

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Table 10. - DEVIATIONS BELOW 60° OF I

| Steel No. & Cond. | Test Temp. °F | 1/4" Weld Temperature, °F 70° | 10° | 0° | -10° | -20° | Rating | Rank | 1/2" Weld Temperature, °F 70° | 10° | 0° | -10° | -20° | Rating | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 139 AR | 70 | -- | 26/2 | 21 | 0/2 | 3/3 | -- | -- | 0/3 | 4/1 | 6/2 | 5/2 | 1/2 | 0x | |
| | 10 | 0 | | 25 | | 1 | | | 19 | | 36 | | 0 | | |
| | 0 | 0 | | 0 | | 9 | | | 16 | | 23 | | 9 | | |
| | -10 | 0 | | 8 | | 18 | | | 68 | | 68 | | 38 | | |
| | -20 | 3 | | 45 | | 26 | | | 33 | | 37 | | 63 | | |
| | Total | All Temperatures 186/59 | | | | | 316x | 6 | | | | | 408/58 | 700x | |
| 139 M | 70 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 0/2 | 0/2 | 0/2 | 9/2 | 0 | |
| | 10 | 0 | | 3 | | 0 | | | 9 | | 0 | | 3 | | |
| | 0 | 0 | | 0 | | 0 | | | 12 | | 3 | | 11 | | |
| | -10 | 0 | | 0 | | 0 | | | 8 | | 40 | | 0 | | |
| | -20 | 0 | | 0 | | 0 | | | 37 | | 17 | | 5 | | |
| | Total | All Temperatures 3/68 | | | | | 4 | 9 | | | | | 154/60 | 257x | |
| 144 AR | 70 | 1 | 28 | 50 | 11 | 23 | 25 | 9 | 20 | 24 | 17 | 4 | 14 | 500 | |
| | 10 | 43 | | 48 | | 32 | | | 15 | | 2 | | 6 | | |
| | 0 | 32 | | 60 | | 52 | | | 0 | | 4 | | 4 | | |
| | -10 | 28 | | 34 | | 19 | | | 2 | | 6 | | 1 | | |
| | -20 | 30 | | 37 | | 38 | | | 10 | | 0 | | 8 | | |
| | Total | All Temperatures 566/68 | | | | | 832 | 1 | | | | | 137/68 | 202 | |
| 144 M | 70 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 5 | 0 | 1 | 0 | 0 | |
| | 10 | 0 | | 1 | | 16 | | | 2 | | 0 | | 0 | | |
| | 0 | 1 | | 8 | | 35 | | | 0 | | 0 | | 0 | | |
| | -10 | 3 | | 6 | | 28 | | | 0 | | 0 | | 0 | | |
| | -20 | 19 | | 0 | | 0 | | | 0 | | 0 | | 19 | | |
| | Total | All Temperatures 117/68 | | | | | 172 | 8 | | | | | 27/68 | 40 | |
| 146 AR | 70 | 0 | - | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 10 | 0 | | 0 | | 0 | | | 0 | | 0 | | 0 | | |
| | 0 | 0 | | 0 | | 0 | | | 0 | | 9 | | 5 | | |
| | -10 | 3 | | 15 | | 0 | | | 0 | | 0 | | 2 | | |
| | -20 | 0 | | 0 | | 0 | | | 0 | | 0 | | 9 | | |
| | Total | All Temperatures 18/64 | | | | | 28 | 9 | | | | | 25/68 | 37 | |
| 146 M | 70 | 20 | 0 | 0 | 0 | 0 | 500 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 10 | 0 | | 0 | | 5 | | | 0 | | 0 | | 0 | | |
| | 0 | 0 | | 0 | | 0 | | | 0 | | 0 | | 2 | | |
| | -10 | 0 | | 0 | | 0 | | | 0 | | 28 | | 0 | | |
| | -20 | 0 | | 0 | | 0 | | | 5 | | 0 | | 0 | | |
| | Total | All Temperatures 25/68 | | | | | 37 | 9 | | | | | 35/68 | 52 | |
| 147 AR | 70 | 2 | 0 | 2 | 1 | 0 | 50 | 9 | 0 | 19 | 12 | 3 | 8 | 0 | |
| | 10 | 0 | | 3 | | 3 | | | 0 | | 0 | | 0 | | |
| | 0 | 3 | | 0 | | 0 | | | 0 | | 0 | | 0 | | |
| | -10 | 8 | | 3 | | 0 | | | 1 | | 11 | | 16 | | |
| | -20 | 8 | | 0 | | 1 | | | 0 | | 2 | | 19 | | |
| | Total | All Temperatures 34/68 | | | | | 50 | 9 | | | | | 91/68 | 134 | |
| 147 M | 70 | 8 | 0 | 0 | 0 | 0 | 200 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 10 | 4 | | 9 | | 1 | | | 0 | | 0 | | 0 | | |
| | 0 | 0 | | 0 | | 0 | | | 0 | | 0 | | 0 | | |
| | -10 | 0 | | 0 | | 2 | | | 0 | | 0 | | 0 | | |
| | -20 | 0 | | 0 | | 0 | | | 16 | | 0 | | 0 | | |
| | Total | All Temperatures 24/68 | | | | | 35 | 9 | | | | | 16/68 | 24 | |
| 149 AR | 70 | 6 | 0 | 13 | 15 | 15 | 150 | 8 | 0 | 2 | 1 | 0 | 0 | 0 | |
| | 10 | 2 | | 7 | | 48 | | | 0 | | 23 | | 19 | | |
| | 0 | - | | 3 | | 9 | | | 2 | | 0 | | 0 | | |
| | -10 | - | | 2 | | 3 | | | 0 | | 15 | | 42 | | |
| | -20 | - | | 20 | | 16 | | | 0 | | 23 | | 7 | | |
| | Total | All Temperatures 159/56 | | | | | 284x | 7 | | | | | 134/68 | 197 | |
| 149 M | 70 | 0 | 3 | 0 | 9 | 0 | 0 | 10 | 0 | 0 | 1 | 0 | 0 | 0 | |
| | 10 | - | | 0 | | 8 | | | 0 | | 0 | | 20 | | |
| | 0 | - | | 1 | | 35 | | | 5 | | 10 | | 16 | | |
| | -10 | - | | 30 | | 12 | | | 4 | | 16 | | 27 | | |
| | -20 | - | | 55 | | 77 | | | 0 | | 31 | | 12 | | |
| | Total | All Temperatures 230/52 | | | | | 442x | 5 | | | | | 142/68 | 209 | |
| 150 AR | 70 | 7 | 18 | 41 | 26 | 7 | 175 | 8 | 0 | 7 | 1 | 15 | 29 | 0 | |
| | 10 | 5 | | 78 | | 0 | | | 0 | | 0 | | 0 | | |
| | 0 | 28 | | 0 | | 1 | | | 7 | | 8 | | 6 | | |
| | -10 | 22 | | 6 | | 14 | | | 15 | | 8 | | 12 | | |
| | -20 | 28 | | 14 | | 16 | | | 16 | | 12 | | 6 | | |
| | Total | All Temperatures 311/68 | | | | | 457 | 5 | | | | | 142/68 | 209 | |
| 150 M | 70 | 0 | 24 | 20 | 3 | 42 | 0 | 10 | 0 | 1 | 0 | 2 | 0 | 0 | |
| | 10 | 0 | | 0 | | 0 | | | 0 | | 0 | | 47 | | |
| | 0 | 0 | | 4 | | 5 | | | 0 | | 0 | | 0 | | |
| | -10 | 2 | | 5 | | 6 | | | 0 | | 0 | | 0 | | |
| | -20 | 6 | | 21 | | 4 | | | 11 | | 0 | | 71 | | |
| | Total | All Temperatures 142/68 | | | | | 209 | 7 | | | | | 132/68 | 194 | |

Determination of Rank

| Range Subdivisions | 0 | 1-100 | 101-200 | 201-300 | 301-400 | 401-500 |
|---|---|---|---|---|---|---|
| Rank Numbers | 10 | 9 | 8 | 7 | 6 | 5 |

W 60° OF INDIVIDUAL ANGLES.

| Rating | Rank | 3/4" Weld Temperature, °F 70° | 10° | 0° | -10° | -20° | Rating | Rank | All Sizes Combined W & T at 70°F Total | Rating | Rank | W & T All Temp. Total | Rating | Rank | Steel No. & Cond. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0x | 10 | 0<br>0<br>0<br>0<br>14 | 0/1 | 0/1<br>0<br>0<br>37<br>7 | 0/1 | 0<br>0<br>10<br>0<br>8 | 0 | 10 | 0/7 | 0x | 10 | | | | 139 AR |
| 700x | 3 | | | | | 76/59 | 129x | 8 | | | | 668/176 | 380x | 6 | |
| 0 | 10 | 0<br>0<br>0<br>0<br>0 | 0/3 | 0<br>0<br>7<br>33<br>34 | 0 | 0<br>0<br>0<br>30<br>2 | 0 | 10 | 0/12 | 0 | 10 | | | | 139 M |
| 257x | 7 | | | | | 106/67 | 158 | 8 | | | | 263/195 | 135 | 8 | |
| 500 | 5 | 37<br>11<br>6<br>21<br>11 | 39 | 46<br>5<br>17<br>12<br>48 | 46 | 37<br>4<br>6<br>17<br>22 | 925 | 0 | 58/12 | 483 | 5 | | | | 144 AR |
| 202 | 7 | | | | | 385/68 | 567 | 4 | | | | 1088/204 | 533 | 4 | |
| 0 | 10 | 1<br>0<br>1<br>17<br>0 | 9 | 9<br>0<br>5<br>11<br>2 | 7 | 0<br>0<br>0<br>3<br>10 | 25 | 9 | 1/12 | 8 | 9 | | | | 144 M |
| 40 | 9 | | | | | 75/68 | 110 | 8 | | | | 219/204 | 107 | 8 | |
| 0 | 10 | 0<br>0<br>0<br>0<br>0 | 0 | 0<br>1<br>0<br>0<br>0 | 0 | 1<br>0<br>5<br>2<br>0 | 0 | 10 | 0/12 | 0 | 10 | | | | 146 AR |
| 37 | 9 | | | | | 9/68 | 13 | 9 | | | | 52/200 | 26 | 9 | |
| 0 | 10 | 0<br>0<br>0<br>0<br>10 | 0 | 0<br>0<br>0<br>0<br>1 | 0 | 0<br>0/2<br>0<br>0<br>0 | 0 | 10 | 20/12 | 167 | 8 | | | | 146 M |
| 52 | 9 | | | | | 11/66 | 17 | 9 | | | | 71/202 | 35 | 9 | |
| 0 | 10 | 0<br>6<br>0<br>0<br>0 | 6 | 0<br>0<br>1<br>36<br>25 | 0 | 0<br>1<br>0<br>26<br>48 | 0 | 10 | 2/12 | 17 | 9 | | | | 147 AR |
| 134 | 8 | | | | | 145/68 | 213 | 7 | | | | 270/204 | 132 | 8 | |
| 0 | 10 | 0<br>12<br>0<br>2<br>9/3 | 0 | 3<br>0<br>10<br>0<br>0 | 0 | 0<br>0<br>0<br>0<br>11 | 0 | 10 | 8/12 | 67 | 9 | | | | 147 M |
| 24 | 9 | | | | | 47/67 | 70 | 9 | | | | 87/203 | 43 | 9 | |
| 0 | 10 | 0<br>3<br>10<br>3<br>32 | 0 | 9<br>0<br>0<br>16<br>24 | 0 | 0<br>27<br>35<br>20<br>19 | 0 | 10 | 6/12 | 50 | 9 | | | | 149 AR |
| 197 | 8 | | | | | 198/68 | 291 | 7 | | | | 491/192 | 256 | 7 | |
| 0 | 10 | 0<br>0<br>2<br>5<br>15 | 0 | 2<br>0<br>0<br>9<br>22 | 2 | 0<br>30<br>0<br>31<br>13 | 0 | 10 | 0/12 | 0 | 10 | | | | 149 M |
| 209 | 7 | | | | | 131/68 | 193 | 8 | | | | 503/188 | 268 | 7 | |
| 0 | 10 | 40<br>0<br>2<br>37<br>44 | 0 | 0<br>25<br>24<br>5<br>29 | 0 | 0<br>2<br>3<br>14<br>11 | 1000 | 0 | 47/12 | 392 | 6 | | | | 150 AR |
| 209 | 7 | | | | | 236/68 | 347 | 6 | | | | 689/204 | 338 | 6 | |
| 0 | 10 | 0<br>0<br>2<br>6<br>21 | 0 | 0<br>1<br>2<br>9<br>2 | 0 | 0<br>9<br>11<br>12<br>0 | 0 | 10 | 0/12 | 0 | 10 | | | | 150 M |
| 194 | 8 | | | | | 75/68 | 110 | 8 | | | | 349/204 | 171 | 8 | |

f Rank

| 401-500 | 501-600 | 601-700 | 701-800 | 801-900 | 901 and over | Range Subdivisions Rank Numbers |
|---|---|---|---|---|---|---|
| 5 | 4 | 3 | 2 | 1 | 0 | |

UNIV. OF MICH.

Table 11. PLATE FAILURE

| Steel No. & Cond. | Test Temp. °F | 1/4" Weld Temp. °F 70 | 10 | 0 | -10 | -20 | 1/4" Failures Tot. | % | 1/2" Weld Temp. °F 70 | 10 | 0 | -10 | -20 | 1/2" Failures Tot. | % | 70 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 139 AR | 70 | 4 | 4 | 4 | 2/2 | 4 | 18x | 100 | 4 | 2 | 4 | 4 | 3 | 17 | 85 | 0 |
| | 10 | 3 | | 4 | | 4 | 11 | 92 | 4 | | 4 | | 4 | 12 | 100 | 2 |
| | 0 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 1 |
| | -10 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 2 |
| | -20 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 3 |
| Total Failed | | 19 | 4 | 20 | 2 | 20 | 65 | | 20 | 2 | 20 | 4 | 19 | 65 | | 8 |
| Total Tested | | | | | x | | 66 | | | | | | | 68 | | |
| % Failed | | 95 | | 100 | | 100 | | 98 | 100 | | 100 | | 95 | | 96 | 40 |
| Rank | | | | | | | | 0 | | | | | | | 0 | |
| 139 M | 70 | 3 | 0 | 0 | 1 | 1 | 5 | 25 | 4 | 2 | 3 | 1 | 1 | 11 | 55 | 0 |
| | 10 | 1 | | 4 | | 1 | 6 | 50 | 4 | | 4 | | 3 | 11 | 92 | 2 |
| | 0 | 2 | | 1 | | 2 | 5 | 42 | 2 | | 3 | | 3 | 8 | 67 | 2 |
| | -10 | 1 | | 3 | | 2 | 6 | 50 | 3 | | 4 | | 2 | 9 | 75 | 2 |
| | -20 | 2 | | 3 | | 4 | 9 | 75 | 3 | | 4 | | 4 | 11 | 92 | 1 |
| Total Failed | | 9 | 0 | 11 | 1 | 10 | 31 | | 16 | 2 | 18 | 1 | 13 | 50 | | 7 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 45 | | 55 | | 50 | | 46 | 80 | | 90 | | 65 | | 74 | 35 |
| Rank | | | | | | | | 5 | | | | | | | 2 | |
| 144 AR | 70 | 4 | 4 | 4 | 4 | 4 | 20 | 100 | 4 | 4 | 3 | 4 | 4 | 19 | 95 | 2 |
| | 10 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 2 |
| | 0 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 4 |
| | -10 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 2 |
| | -20 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 4 | | 4 | 12 | 100 | 3 |
| Total Failed | | 20 | 4 | 20 | 4 | 20 | 68 | | 20 | 4 | 19 | 4 | 20 | 67 | | 13 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 100 | | 100 | | 100 | | 100 | 100 | | 95 | | 100 | | 99 | 65 |
| Rank | | | | | | | | 0 | | | | | | | 0 | |
| 144 M | 70 | 0 | 3 | 4 | 3 | 4 | 14 | 70 | 0 | 4 | 4 | 3 | 3 | 14 | 70 | 2 |
| | 10 | 3 | | 4 | | 4 | 11 | 92 | 1 | | 4 | | 2 | 7 | 58 | 0 |
| | 0 | 0 | | 2 | | 3 | 5 | 42 | 1 | | 4 | | 2 | 7 | 58 | 0 |
| | -10 | 4 | | 2 | | 4 | 10 | 83 | 1 | | 4 | | 4 | 9 | 75 | 3 |
| | -20 | 2 | | 1 | | 1 | 4 | 33 | 2 | | 4 | | 4 | 10 | 83 | 4 |
| Total Failed | | 9 | 3 | 13 | 3 | 16 | 44 | | 5 | 4 | 20 | 3 | 15 | 47 | | 9 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 45 | | 65 | | 80 | | 65 | 25 | | 100 | | 75 | | 69 | 45 |
| Rank | | | | | | | | 3 | | | | | | | 3 | |
| 146 AR | 70 | 1 | - | 4 | 0 | 0 | 5x | 31 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 0 | | 2 | | 0 | 2 | 17 | 2 | | 2 | | 1 | 5 | 42 | 2 |
| | 0 | 0 | | 1 | | 1 | 2 | 17 | 2 | | 4 | | 2 | 8 | 67 | 4 |
| | -10 | 0 | | 1 | | 1 | 2 | 17 | 1 | | 4 | | 4 | 9 | 75 | 3 |
| | -20 | 1 | | 2 | | 2 | 5 | 42 | 3 | | 2 | | 4 | 9 | 75 | 3 |
| Total Failed | | 2 | x | 10 | 0 | 4 | 16 | | 8 | 0 | 12 | 0 | 11 | 31 | | 12 |
| Total Tested | | | | | | | 64 | | | | | | | 68 | | |
| % Failed | | 10 | | 50 | | 20 | | 25 | 40 | | 60 | | 55 | | 46 | 60 |
| Rank | | | | | | | | 7 | | | | | | | 5 | |
| 146 M | 70 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 5 | 0 |
| | 10 | 1 | | 0 | | 0 | 1 | 8 | 1 | | 1 | | 1 | 3 | 25 | 0 |
| | 0 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 1 | | 0 | 1 | 8 | 0 |
| | -10 | 0 | | 0 | | 0 | 0 | 0 | 1 | | 3 | | 3 | 7 | 58 | 3 |
| | -20 | 1 | | 0 | | 0 | 1 | 8 | 2 | | 3 | | 2 | 7 | 58 | 3 |
| Total Failed | | 2 | 0 | 0 | 0 | 0 | 2 | | 5 | 0 | 8 | 0 | 6 | 19 | | 6 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 10 | | 0 | | 0 | | 3 | 25 | | 40 | | 30 | | 28 | 30 |
| Rank | | | | | | | | 9 | | | | | | | 7 | |
| 147 AR | 70 | 4 | 4 | 4 | 4 | 4 | 20 | 100 | 1 | 0 | 0 | 4 | 2 | 7 | 35 | 2 |
| | 10 | 4 | | 4 | | 3 | 11 | 92 | 2 | | 3 | | 0 | 5 | 42 | 4 |
| | 0 | 4 | | 4 | | 4 | 12 | 100 | 0 | | 3 | | 2 | 5 | 42 | 4 |
| | -10 | 4 | | 4 | | 4 | 12 | 100 | 4 | | 3 | | 4 | 11 | 92 | 3 |
| | -20 | 4 | | 3 | | 4 | 11 | 92 | 4 | | 4 | | 3 | 11 | 92 | 4 |
| Total Failed | | 20 | 4 | 19 | 4 | 19 | 66 | | 11 | 0 | 13 | 4 | 11 | 39 | | 17 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 100 | | 95 | | 95 | | 97 | 55 | | 65 | | 55 | | 57 | 85 |
| Rank | | | | | | | | 0 | | | | | | | 4 | |
| 147 M | 70 | 0 | 0 | 3 | 0 | 2 | 5 | 25 | 0 | 1 | 0 | 1 | 0 | 2 | 10 | 0 |
| | 10 | 1 | | 4 | | 1 | 6 | 50 | 1 | | 0 | | 1 | 2 | 17 | 2 |
| | 0 | 0 | | 1 | | 0 | 1 | 8 | 2 | | 1 | | 1 | 4 | 33 | 3 |
| | -10 | 1 | | 2 | | 2 | 5 | 42 | 4 | | 1 | | 2 | 7 | 58 | 3 |
| | -20 | 0 | | 3 | | 1 | 4 | 33 | 4 | | 3 | | 1 | 8 | 67 | 4 |
| Total Failed | | 2 | 0 | 13 | 0 | 6 | 21 | | 11 | 1 | 5 | 1 | 5 | 23 | | 12 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 10 | | 65 | | 30 | | 31 | 55 | | 25 | | 25 | | 34 | 60 |
| Rank | | | | | | | | 6 | | | | | | | 6 | |
| 149 AR | 70 | 4 | 4 | 4 | 4 | 4 | 20 | 100 | 1 | 4 | 0 | 2 | 0 | 7 | 35 | 1 |
| | 10 | 4 | | 2 | | 4 | 10 | 83 | 3 | | 4 | | 3 | 10 | 83 | 4 |
| | 0 | - | | 4 | | 4 | 8x | 100 | 2 | | 4 | | 3 | 9 | 75 | 4 |
| | -10 | - | | 4 | | 4 | 8x | 100 | 4 | | 4 | | 4 | 12 | 100 | 4 |
| | -20 | - | | 4 | | 4 | 8x | 100 | 3 | | 4 | | 4 | 11 | 92 | 4 |
| Total Failed | | 8 | 4 | 18 | 4 | 20 | 54 | | 13 | 4 | 16 | 2 | 14 | 49 | | 17 |
| Total Tested | | x | | | | | 56 | | | | | | | 68 | | |
| % Failed | | 100 | | 90 | | 100 | | 96x | 65 | | 80 | | 70 | | 72 | 85 |
| Rank | | | | | | | | 0 | | | | | | | 2 | |
| 149 M | 70 | 0 | 4 | 4 | 4 | 4 | 16 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | - | | 1 | | 4 | 5x | 63 | 0 | | 3 | | 3 | 6 | 50 | 1 |
| | 0 | - | | 3 | | 4 | 7x | 87 | 3 | | 4 | | 4 | 11 | 92 | 3 |
| | -10 | - | | 4 | | 3 | 7x | 87 | 3 | | 4 | | 4 | 11 | 92 | 3 |
| | -20 | - | | 4 | | 4 | 8x | 100 | 3 | | 4 | | 4 | 11 | 92 | 3 |
| Total Failed | | 0 | 4 | 16 | 4 | 19 | 43 | | 9 | 0 | 15 | 0 | 15 | 39 | | 10 |
| Total Tested | | x | | | | | 52 | | | | | | | 68 | | |
| % Failed | | 0 | | 80 | | 95 | | 83x | 45 | | 75 | | 75 | | 57 | 50 |
| Rank | | | | | | | | 1 | | | | | | | 4 | |
| 150 AR | 70 | 4 | 3 | 4 | 4 | 3 | 18 | 90 | 4 | 0 | 0 | 0 | 0 | 4 | 20 | 2 |
| | 10 | 4 | | 4 | | 2 | 10 | 83 | 0 | | 0 | | 0 | 0 | 0 | 2 |
| | 0 | 4 | | 4 | | 4 | 12 | 100 | 0 | | 0 | | 3 | 3 | 25 | 1 |
| | -10 | 4 | | 4 | | 4 | 12 | 100 | 0 | | 3 | | 2 | 5 | 42 | 3 |
| | -20 | 4 | | 4 | | 4 | 12 | 100 | 1 | | 2 | | 4 | 7 | 58 | 4 |
| Total Failed | | 20 | 3 | 20 | 4 | 17 | 64 | | 5 | 0 | 5 | 0 | 9 | 19 | | 12 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 100 | | 100 | | 85 | | 94 | 25 | | 25 | | 45 | | 28 | 60 |
| Rank | | | | | | | | 0 | | | | | | | 7 | |
| 150 M | 70 | 0 | 4 | 0 | 2 | 4 | 10 | 50 | 3 | 0 | 0 | 0 | 0 | 3 | 15 | 0 |
| | 10 | 0 | | 0 | | 1 | 1 | 8 | 0 | | 0 | | 1 | 1 | 8 | 0 |
| | 0 | 1 | | 1 | | 1 | 3 | 25 | 0 | | 0 | | 1 | 1 | 8 | 2 |
| | -10 | 1 | | 0 | | 1 | 2 | 17 | 0 | | 2 | | 2 | 4 | 33 | 3 |
| | -20 | 1 | | 0 | | 1 | 2 | 17 | 3 | | 1 | | 3 | 7 | 58 | 3 |
| Total Failed | | 3 | 4 | 1 | 2 | 8 | 18 | | 6 | 0 | 3 | 0 | 7 | 16 | | 8 |
| Total Tested | | | | | | | 68 | | | | | | | 68 | | |
| % Failed | | 15 | | 5 | | 40 | | 26 | 30 | | 15 | | 35 | | 24 | 40 |
| Rank | | | | | | | | 7 | | | | | | | 7 | |

Determination of Rank

| Range Subdivisions | 0 | 1-10 | 11-20 | 21-30 | 31-40 | 41-50 |
|---|---|---|---|---|---|---|
| Rank Numbers | 10 | 9 | 8 | 7 | 6 | 5 |

TE FAILURES.

| res | 3/4" | | | | | | | All Sizes Combined | | | | | | | | Steel No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Weld Temp. °F | | | | | Failures | | Weld Temp. °F | | | | | Failures | | Welded & Tested at 70°F | |
| % | 70 | 10 | 0 | -10 | -20 | Tot. | % | 70 | 10 | 0 | -10 | -20 | Tot. | % | | |
| 85 | 0 | 3 | 2 | 2 | 1 | 8 | 40 | 8 | | | | | 43x | 74 | | 139 |
| 100 | 2 | | 4 | | 1 | 7 | 58 | | | | | | 30 | 83 | | AR |
| 100 | 1 | | 2 | | 2 | 5 | 42 | | | | | | 29 | 81 | | |
| 100 | 2 | | 4 | | 3 | 9 | 75 | | | | | | 33 | 92 | | |
| 100 | 3 | | 4 | | 3 | 10 | 83 | | | | | | 34 | 94 | | |
| | 8 | 3 | 16 | 2 | 10 | 39 | | 47 | 9 | 56 | 8 | 49 | 169 | | 8 | |
| | | | | | | 68 | | | | | | | 202 | | 12 | |
| 96 | 40 | | 80 | | 50 | | 57 | 78 | | 93 | | 82 | | 84 | 67 | |
| 0 | | | | | | | 4 | | | | | | | 1 | 3 | |
| 55 | 0 | 0 | 1 | 0 | 3 | 4 | 20 | 7 | | | | | 20 | 33 | | 139 |
| 92 | 2 | | 2 | | 2 | 6 | 50 | | | | | | 23 | 64 | | M |
| 67 | 2 | | 3 | | 3 | 8 | 67 | | | | | | 21 | 58 | | |
| 75 | 2 | | 4 | | 4 | 10 | 83 | | | | | | 25 | 69 | | |
| 92 | 1 | | 3 | | 4 | 8 | 67 | | | | | | 28 | 78 | | |
| | 7 | 0 | 13 | 0 | 16 | 36 | | 32 | 2 | 42 | 2 | 39 | 117 | | 7 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 74 | 35 | | 65 | | 80 | | 53 | 53 | | 70 | | 65 | | 57 | 58 | |
| 2 | | | | | | | 4 | | | | | | | 4 | 4 | |
| 95 | 2 | 4 | 4 | 3 | 4 | 17 | 85 | 10 | | | | | 56 | 93 | | 144 |
| 100 | 2 | | 3 | | 3 | 8 | 67 | | | | | | 32 | 89 | | AR |
| 100 | 4 | | 2 | | 4 | 10 | 83 | | | | | | 34 | 94 | | |
| 100 | 2 | | 3 | | 4 | 9 | 75 | | | | | | 33 | 92 | | |
| 100 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 35 | 97 | | |
| | 13 | 4 | 16 | 3 | 19 | 55 | | 53 | 12 | 55 | 11 | 59 | 190 | | 10 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 99 | 65 | | 80 | | 95 | | 81 | 88 | | 92 | | 98 | | 93 | 83 | |
| 0 | | | | | | | 1 | | | | | | | 0 | 1 | |
| 70 | 2 | 0 | 2 | 0 | 0 | 4 | 20 | 2 | | | | | 32 | 53 | | 144 |
| 58 | 0 | | 0 | | 1 | 1 | 8 | | | | | | 19 | 53 | | M |
| 58 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 12 | 33 | | |
| 75 | 3 | | 4 | | 1 | 8 | 67 | | | | | | 27 | 75 | | |
| 83 | 4 | | 4 | | 1 | 9 | 75 | | | | | | 23 | 64 | | |
| | 9 | 0 | 10 | 0 | 3 | 22 | | 23 | 7 | 43 | 6 | 34 | 113 | | 2 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 69 | 45 | | 50 | | 15 | | 32 | 38 | | 72 | | 57 | | 55 | 17 | |
| 3 | | | | | | | 6 | | | | | | | 4 | 8 | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | | | | 5 | 9 | | 146 |
| 42 | 2 | | 4 | | 0 | 6 | 50 | | | | | | 13 | 36 | | AR |
| 67 | 4 | | 4 | | 4 | 12 | 100 | | | | | | 22 | 61 | | |
| 75 | 3 | | 3 | | 4 | 10 | 83 | | | | | | 21 | 58 | | |
| 75 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 25 | 69 | | |
| | 12 | 0 | 15 | 0 | 12 | 39 | | 22 | 0 | 37 | 0 | 27 | 86 | | 1 | |
| | | | | | | 68 | | | | | | | 200 | | 12 | |
| 46 | 60 | | 75 | | 60 | | 57 | 37 | | 62 | | 45 | | 43 | 8 | |
| 5 | | | | | | | 4 | | | | | | | 5 | 9 | |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | | | | 1 | 2 | | 146 |
| 25 | 0 | | 2 | | 1/2 | 3x | 30 | | | | | | 7 | 19 | | M |
| 8 | 0 | | 4 | | 3 | 7 | 58 | | | | | | 8 | 22 | | |
| 58 | 3 | | 3 | | 3 | 9 | 75 | | | | | | 16 | 44 | | |
| 58 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 19 | 53 | | |
| | 6 | 0 | 13 | 0 | 11 | 30 | | 13 | 0 | 21 | 0 | 17 | 51 | | 1 | |
| | | | | | x | 66 | | | | | | | 202 | | 12 | |
| 28 | 30 | | 65 | | 61 | | 45 | 22 | | 35 | | 29 | | 25 | 8 | |
| 7 | | | | | | | 5 | | | | | | | 7 | 9 | |
| 35 | 2 | 4 | 4 | 3 | 4 | 17 | 85 | 7 | | | | | 44 | 73 | | 147 |
| 42 | 4 | | 4 | | 3 | 11 | 92 | | | | | | 27 | 75 | | AR |
| 42 | 4 | | 4 | | 4 | 12 | 100 | | | | | | 29 | 81 | | |
| 92 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 34 | 94 | | |
| 92 | 4 | | 4 | | 4 | 12 | 100 | | | | | | 34 | 94 | | |
| | 17 | 4 | 20 | 3 | 19 | 63 | | 48 | 8 | 52 | 11 | 49 | 168 | | 7 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 57 | 85 | | 100 | | 95 | | 93 | 80 | | 87 | | 82 | | 82 | 58 | |
| 4 | | | | | | | 0 | | | | | | | 1 | 4 | |
| 10 | 0 | 2 | 4 | 3 | 2 | 11 | 55 | 0 | | | | | 18 | 30 | | 147 |
| 17 | 2 | | 4 | | 2 | 8 | 67 | | | | | | 16 | 44 | | M |
| 33 | 3 | | 4 | | 3 | 10 | 83 | | | | | | 15 | 42 | | |
| 58 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 23 | 64 | | |
| 67 | 4 | | 4 | | 3 | 11 | 92 | | | | | | 23 | 64 | | |
| | 12 | 2 | 20 | 3 | 14 | 51 | | 25 | 3 | 38 | 4 | 25 | 95 | | 0 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 34 | 60 | | 100 | | 70 | | 75 | 42 | | 63 | | 42 | | 47 | 0 | |
| 6 | | | | | | | 2 | | | | | | | 5 | 10 | |
| 35 | 1 | 0 | 0 | 0 | 0 | 1 | 5 | 6 | | | | | 28 | 47 | | 149 |
| 83 | 4 | | 3 | | 3 | 10 | 83 | | | | | | 30 | 83 | | AR |
| 75 | 4 | | 4 | | 4 | 12 | 100 | | | | | | 29x | 91 | | |
| 100 | 4 | | 3 | | 4 | 11 | 92 | | | | | | 31x | 97 | | |
| 92 | 4 | | 3 | | 4 | 11 | 92 | | | | | | 30x | 94 | | |
| | 17 | 0 | 13 | 0 | 15 | 45 | | 38 | 8 | 47 | 6 | 49 | 148 | | 6 | |
| | | | | | | 68 | | x | | | | | 192 | | 12 | |
| 72 | 85 | | 65 | | 75 | | 66 | 79 | | 78 | | 82 | | 77 | 50 | |
| 2 | | | | | | | 3 | | | | | | | 2 | 5 | |
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 5 | 0 | | | | | 17 | 28 | | 149 |
| 50 | 1 | | 3 | | 4 | 8 | 67 | | | | | | 19x | 59 | | M |
| 92 | 3 | | 3 | | 2 | 8 | 67 | | | | | | 26x | 81 | | |
| 92 | 3 | | 4 | | 3 | 10 | 83 | | | | | | 28x | 88 | | |
| 92 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 30x | 94 | | |
| | 10 | 0 | 14 | 0 | 14 | 38 | | 19 | 4 | 45 | 4 | 48 | 120 | | 0 | |
| | | | | | | 68 | | x | | | | | 188 | | 12 | |
| 57 | 50 | | 70 | | 70 | | 56 | 43 | | 75 | | 80 | | 64 | 0 | |
| 4 | | | | | | | 4 | | | | | | | 3 | 10 | |
| 20 | 2 | 4 | 4 | 4 | 3 | 17 | 85 | 10 | | | | | 39 | 65 | | 150 |
| 0 | 2 | | 2 | | 4 | 8 | 67 | | | | | | 18 | 50 | | AR |
| 25 | 1 | | 4 | | 4 | 9 | 75 | | | | | | 24 | 67 | | |
| 42 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 28 | 78 | | |
| 58 | 4 | | 4 | | 4 | 12 | 100 | | | | | | 31 | 86 | | |
| | 12 | 4 | 18 | 4 | 19 | 57 | | 37 | 7 | 43 | 8 | 45 | 140 | | 10 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 28 | 60 | | 90 | | 95 | | 84 | 62 | | 72 | | 75 | | 69 | 83 | |
| 7 | | | | | | | 1 | | | | | | | 3 | 1 | |
| 15 | 0 | 0 | 1 | 0 | 0 | 1 | 5 | 3 | | | | | 14 | 23 | | 150 |
| 8 | 0 | | 2 | | 1 | 3 | 25 | | | | | | 5 | 14 | | M |
| 8 | 2 | | 4 | | 0 | 6 | 50 | | | | | | 10 | 28 | | |
| 33 | 3 | | 3 | | 3 | 9 | 75 | | | | | | 15 | 42 | | |
| 58 | 3 | | 4 | | 4 | 11 | 92 | | | | | | 20 | 56 | | |
| | 8 | 0 | 14 | 0 | 8 | 30 | | 17 | 4 | 18 | 2 | 23 | 64 | | 3 | |
| | | | | | | 68 | | | | | | | 204 | | 12 | |
| 24 | 40 | | 70 | | 40 | | 44 | 28 | | 30 | | 38 | | 31 | 25 | |
| 7 | | | | | | | 5 | | | | | | | 6 | 7 | |

k

| 41-50 | 51-60 | 61-70 | 71-80 | 81-90 | 91-100 | Range Subdivisions |
|---|---|---|---|---|---|---|
| 5 | 4 | 3 | 2 | 1 | 0 | Rank Numbers |

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Table 12. - BOND AND

| Steel No. & Cond. | Test Temp. °F | 1/4" Weld Temp. °F 70 | 10 | 0 | -10 | -20 | 1/4" Failures Tot. | % | 1/2" Weld Temp. °F 70 | 10 | 0 | -10 | -20 | 1/2" Failur Tot. | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 139 AR | 70 | 0 | 0 | 0 | 0/2 | 0 | 0x | 0 | 0 | 2 | 0 | 0 | 0 | 2 | |
| | 10 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| | 0 | 0 | | 1 | | 0 | 1 | 8 | 0 | | 0 | | 0 | 0 | |
| | -10 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| | -20 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| Total Failed | | 0 | 0 | 1 | 0 | 0 | 1 | | 0 | 2 | 0 | 0 | 0 | 2 | |
| Total Tested | | | | | x | | 66 | | | | | | | 68 | |
| % Failed | | 0 | | 5 | | 0 | | 2 | 0 | | 0 | | 0 | | |
| Rank | | | | | | | | 9 | | | | | | | |
| 139 N | 70 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 0 | 4 | |
| | 10 | 0 | | 1 | | 0 | 1 | 8 | 0 | | 0 | | 1 | 1 | |
| | 0 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| | -10 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 1 | 1 | |
| | -20 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| Total Failed | | 0 | 0 | 1 | 0 | 0 | 1 | | 0 | 0 | 1 | 3 | 2 | 6 | |
| Total Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 0 | | 5 | | 0 | | 1 | 0 | | 5 | | 10 | | |
| Rank | | | | | | | | 9 | | | | | | | |
| 144 AR | 70 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | |
| | 10 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 1 | | 1 | 2 | |
| | 0 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| | -10 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| | -20 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | |
| Total Failed | | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 1 | 1 | 1 | 3 | |
| Total Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 0 | | 0 | | 0 | | 0 | 0 | | 5 | | 5 | | |
| Rank | | | | | | | | 10 | | | | | | | |
| 144 N | 70 | 0 | 1 | 0 | 0 | 0 | 1 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 10 | 0 | | 0 | | 2 | 2 | 17 | 0 | | 0 | | 0 | 0 | |
| | 0 | 0 | | 0 | | 3 | 3 | 25 | 0 | | 0 | | 0 | 0 | |
| | -10 | 0 | | 3 | | 0 | 3 | 25 | 0 | | 0 | | 0 | 0 | |
| | -20 | 2 | | 1 | | 0 | 3 | 25 | 0 | | 0 | | 0 | 0 | |
| Total Failed | | 2 | 1 | 4 | 0 | 5 | 12 | | 0 | 0 | 0 | 0 | 0 | 0 | |
| Total Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 10 | | 20 | | 25 | | 18 | 0 | | 0 | | 0 | | |
| Rank | | | | | | | | 8 | | | | | | | |
| 146 AR | 70 | 1 | - | 0 | 0 | 1 | 2x | 13 | 0 | 2 | 3 | 1 | 4 | 10 | |
| | 10 | 0 | | 2 | | 1 | 3 | 25 | 1 | | 2 | | 4 | 7 | |
| | 0 | 0 | | 1 | | 1 | 2 | 17 | 3 | | 3 | | 3 | 9 | |
| | -10 | 0 | | 1 | | 3 | 4 | 33 | 1 | | 0 | | 1 | 2 | |
| | -20 | 2 | | 2 | | 2 | 6 | 50 | 0 | | 0 | | 1 | 1 | |
| Total Failed | | 3 | x | 6 | 0 | 8 | 17 | | 5 | 2 | 8 | 1 | 13 | 29 | |
| Total Tested | | | | | | | 64 | | | | | | | 68 | |
| % Failed | | 15 | | 30 | | 40 | | 27 | 25 | | 40 | | 65 | | |
| Rank | | | | | | | | 7 | | | | | | | |
| 146 N | 70 | 1 | | 2 | 0 | 3 | 6 | 30 | 0 | 2 | 3 | 0 | 3 | 8 | |
| | 10 | 0 | | 0 | | 1 | 1 | 8 | 1 | | 4 | | 2 | 7 | |
| | 0 | 2 | | 0 | | 0 | 2 | 17 | 2 | | 2 | | 2 | 6 | |
| | -10 | 1 | | 0 | | 0 | 1 | 8 | 0 | | 2 | | 1 | 3 | |
| | -20 | 2 | | 1 | | 0 | 3 | 25 | 0 | | 0 | | 2 | 2 | |
| Total Failed | | 6 | 0 | 3 | 0 | 4 | 13 | | 3 | 2 | 11 | 0 | 10 | 26 | |
| TOtal Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 30 | | 15 | | 20 | | 19 | 15 | | 55 | | 50 | | |
| Rank | | | | | | | | 8 | | | | | | | |
| 147 AR | 70 | 0 | 0 | 0 | 2 | 0 | 2 | 10 | 4 | 4 | 4 | 3 | 4 | 19 | |
| | 10 | 1 | | 0 | | 0 | 1 | 8 | 2 | | 2 | | 4 | 8 | |
| | 0 | 0 | | 0 | | 0 | 0 | 0 | 3 | | 2 | | 4 | 9 | |
| | -10 | 0 | | 0 | | 0 | 0 | 0 | 0 | | 1 | | 2 | 3 | |
| | -20 | 0 | | 2 | | 2 | 4 | 33 | 0 | | 0 | | 1 | 1 | |
| Total Failed | | 1 | 0 | 2 | 2 | 2 | 7 | | 9 | 4 | 9 | 3 | 15 | 40 | |
| TOtal Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 5 | | 10 | | 10 | | 10 | 45 | | 45 | | 75 | | |
| Rank | | | | | | | | 9 | | | | | | | |
| 147 N | 70 | 3 | 0 | 1 | 1 | 0 | 5 | 25 | 2 | 3 | 4 | 4 | 4 | 17 | |
| | 10 | 3 | | 1 | | 1 | 5 | 42 | 4 | | 4 | | 3 | 11 | |
| | 0 | 0 | | 4 | | 1 | 5 | 42 | 3 | | 4 | | 2 | 9 | |
| | -10 | 1 | | 1 | | 1 | 3 | 25 | 2 | | 4 | | 3 | 9 | |
| | -20 | 1 | | 4 | | 2 | 7 | 58 | 0 | | 1 | | 2 | 3 | |
| Total Failed | | 8 | 0 | 11 | 1 | 5 | 25 | | 11 | 3 | 17 | 4 | 14 | 49 | |
| Total Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 40 | | 55 | | 25 | | 37 | 55 | | 85 | | 70 | | |
| Rank | | | | | | | | 6 | | | | | | | |
| 149 AR | 70 | 0 | 3 | 0 | 0 | 0 | 3 | 15 | 2 | 0 | 0 | 0 | 4 | 6 | |
| | 10 | 0 | | 2 | | 0 | 2 | 17 | 0 | | 0 | | 0 | 0 | |
| | 0 | - | | 0 | | 0 | 0x | 0 | 0 | | 0 | | 0 | 0 | |
| | -10 | - | | 0 | | 0 | 0x | 0 | 0 | | 0 | | 0 | 0 | |
| | -20 | - | | 0 | | 0 | 0x | 0 | 0 | | 0 | | 0 | 0 | |
| Total Failed | | 0 | 3 | 2 | 0 | 0 | 5 | | 2 | 0 | 0 | 0 | 4 | 6 | |
| Total Tested | | x | | | | | 56 | | | | | | | 68 | |
| % Failed | | 0 | | 10 | | 0 | | 9x | 10 | | 0 | | 20 | | |
| Rank | | | | | | | | 9 | | | | | | | |
| 149 N | 70 | 0 | 3 | 0 | 0 | 0 | 3 | 15 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 10 | - | | 3 | | 0 | 3x | 38 | 0 | | 0 | | 0 | 0 | |
| | 0 | - | | 1 | | 0 | 1x | 13 | 0 | | 0 | | 0 | 0 | |
| | -10 | - | | 0 | | 0 | 0x | 0 | 0 | | 0 | | 0 | 0 | |
| | -20 | - | | 0 | | 0 | 0x | 0 | 0 | | 0 | | 0 | 0 | |
| Total Failed | | 0 | 3 | 4 | 0 | 0 | 7 | | 0 | 0 | 0 | 0 | 0 | 0 | |
| Total Tested | | x | | | | | 52 | | | | | | | 68 | |
| % Failed | | 0 | | 20 | | 0 | | 13x | 0 | | 0 | | 0 | | |
| Rank | | | | | | | | 8 | | | | | | | |
| 150 AR | 70 | 0 | 1 | 0 | 0 | 0 | 1 | 5 | 2 | 4 | 4 | 4 | 4 | 18 | |
| | 10 | 0 | | 0 | | 2 | 2 | 17 | 4 | | 4 | | 4 | 12 | |
| | 0 | 0 | | 0 | | 0 | 0 | 0 | 4 | | 4 | | 1 | 9 | |
| | -10 | 0 | | 0 | | 0 | 0 | 0 | 4 | | 2 | | 2 | 8 | |
| | -20 | 0 | | 0 | | 0 | 0 | 0 | 3 | | 2 | | 0 | 5 | |
| Total Failed | | 0 | 1 | 0 | 0 | 2 | 3 | | 17 | 14 | 16 | 4 | 11 | 52 | |
| Total Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 0 | | 0 | | 10 | | 4 | 85 | | 80 | | 55 | | |
| Rank | | | | | | | | 9 | | | | | | | |
| 150 N | 70 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 3 | 4 | 3 | 16 | |
| | 10 | 2 | | 0 | | 3 | 5 | 42 | 1 | | 2 | | 3 | 6 | |
| | 0 | 1 | | 0 | | 1 | 2 | 17 | 1 | | 2 | | 2 | 5 | |
| | -10 | 0 | | 2 | | 3 | 5 | 42 | 3 | | 4 | | 2 | 6 | |
| | -20 | 1 | | 1 | | 1 | 3 | 25 | 0 | | 1 | | 1 | 2 | |
| Total Failed | | 4 | 0 | 3 | | 8 | 15 | | 7 | 4 | 9 | 4 | 11 | 35 | |
| Total Tested | | | | | | | 68 | | | | | | | 68 | |
| % Failed | | 20 | | 15 | | 40 | | 22 | 35 | | 45 | | 55 | | |
| Rank | | | | | | | | 7 | | | | | | | |

Determinat

| Range Subdivisions | 0 | 1-10 | 11-20 | 21-30 | 31-40 |
|---|---|---|---|---|---|
| Rank Numbers | 10 | 9 | 8 | 7 | 6 |

BOND AND WELD FAILURES.

| Failures | | 3/4" Weld Temp. °F | | | | | Failures | | All Sizes Combined Weld Temp. °F | | | | | Failures | | Welded & Tested at 70°F | Steel No. & Cond. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tot. | % | 70 | 10 | 0 | -10 | -20 | Tot. | % | 70 | 10 | 0 | -10 | -20 | Tot. | % | | |
| 2 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | 2 | 3 | | 139 |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 0 | 0 | | AR |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 1 | 3 | | |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 0 | 0 | | |
| 0 | 0 | 0 | | 1 | | 0 | 1 | 8 | | | | | | 1 | 3 | | |
| 2 | | 0 | 0 | 1 | 0 | 0 | 1 | | 0 | 2 | 2 | 0 | 0 | 4 | | 0 | |
| 68 | | | | | | | 68 | | | | | | | 202 | | 12 | |
| | 3 | 0 | | 5 | | 0 | | 1 | 0 | | 3 | | 0 | | 2 | 0 | |
| | 9 | | | | | | | 9 | | | | | | | 9 | 10 | |
| 4 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | 4 | 7 | | 139 |
| 1 | 8 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 2 | 6 | | N |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 0 | 0 | | |
| 1 | 8 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 1 | 3 | | |
| 0 | | 0 | | 0 | | 0 | 0 | | | | | | | 0 | 0 | | |
| 6 | | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 2 | 3 | 2 | 7 | | 0 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 9 | 0 | | 0 | | 0 | | 0 | 0 | | 3 | | 3 | | 3 | 0 | |
| | 9 | | | | | | | 10 | | | | | | | 9 | 10 | |
| 1 | 5 | 1 | 0 | 0 | 0 | 1 | 2 | 10 | 1 | | | | | 3 | 5 | | 144 |
| 2 | 17 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 2 | 6 | | AR |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 0 | 0 | | |
| 0 | 0 | 0 | | 00 | | 0 | 0 | 0 | | | | | | 0 | 8 | | |
| 0 | 0 | 3 | | 0 | | 0 | 3 | 25 | | | | | | 3 | | | |
| 3 | | 4 | 0 | 0 | 0 | 1 | 5 | | 4 | 0 | 1 | 1 | 2 | 8 | | 1 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 4 | 20 | | 0 | | 5 | | 7 | 7 | | 2 | | 3 | | 4 | 8 | |
| | 9 | | | | | | | 9 | | | | | | | 9 | 9 | |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 5 | 1 | | | | | 2 | 3 | | 144 |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 2 | 6 | | N |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 3 | 8 | | |
| 0 | 0 | 1 | | 0 | | 0 | 1 | 8 | | | | | | 4 | 11 | | |
| 0 | 0 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 3 | 8 | | |
| 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | | 4 | 1 | 4 | 0 | 5 | 14 | | 1 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 0 | 10 | | 0 | | 0 | | 3 | 7 | | 7 | | 8 | | 7 | 8 | |
| | 10 | | | | | | | 9 | | | | | | | 9 | 9 | |
| 10 | 50 | 0 | 2 | 0 | 0 | 3 | 5 | 25 | 1 | | | | | 17x | 30 | | 146 |
| 7 | 58 | 2 | | 0 | | 1 | 3 | 25 | | | | | | 13 | 36 | | AR |
| 9 | 75 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 11 | 31 | | |
| 2 | 17 | 1 | | 1 | | 0 | 2 | 17 | | | | | | 8 | 22 | | |
| 1 | 8 | 1 | | 0 | | 0 | 1 | 8 | | | | | | 8 | 22 | | |
| 29 | | 4 | 2 | 1 | 0 | 4 | 11 | | 12 | 4 | 15 | 1 | 25 | 57 | | 1 | |
| 68 | | | | | | | 68 | | | x | | | | 200 | | 12 | |
| | 43 | 20 | | 5 | | 20 | | 16 | 20 | | 25 | | 42 | | 29 | 8 | |
| | 5 | | | | | | | 8 | | | | | | | 7 | 9 | |
| 8 | 40 | 4 | 0 | 0 | 1 | 0 | 5 | 25 | 5 | | | | | 19 | 32 | | 146 |
| 7 | 58 | 0 | | 0 | | 0/2 | 0x | 0 | | | | | | 8x | 24 | | N |
| 6 | 50 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 8 | 22 | | |
| 3 | 25 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 4 | 11 | | |
| 2 | 17 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 5 | 14 | | |
| 26 | | 4 | 0 | 0 | 1 | 0 | 5 | | 13 | 2 | 14 | 1 | 14 | 44 | | 5 | |
| 68 | | | | | | x | 66 | | | | | | x | 202 | | 12 | |
| | 38 | 20 | | 0 | | 0 | | 8 | 22 | | 23 | | 24 | | 22 | 42 | |
| | 6 | | | | | | | 9 | | | | | | | 7 | 5 | |
| 19 | 95 | 2 | 0 | 0 | 0 | 1 | 3 | 15 | 6 | | | | | 24 | 40 | | 147 |
| 8 | 67 | 1 | | 0 | | 0 | 1 | 8 | | | | | | 10 | 28 | | AR |
| 9 | 75 | 0 | | 0 | | 1 | 1 | 8 | | | | | | 10 | 28 | | |
| 3 | 25 | 2 | | 0 | | 0 | 2 | 17 | | | | | | 5 | 14 | | |
| 1 | 8 | 3 | | 0 | | 0 | 3 | 25 | | | | | | 8 | 22 | | |
| 40 | | 8 | 0 | 0 | 0 | 2 | 10 | | 18 | 4 | 11 | 5 | 19 | 57 | | 6 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 59 | 40 | | 0 | | 10 | | 15 | 30 | | 18 | | 32 | | 28 | 50 | |
| | 4 | | | | | | | 8 | | | | | | | 7 | 5 | |
| 17 | 85 | 2 | 2 | 0 | 2 | 1 | 7 | 35 | 7 | | | | | 29 | 48 | | 147 |
| 11 | 92 | 2 | | 0 | | 2 | 4 | 33 | | | | | | 20 | 56 | | N |
| 9 | 75 | 1 | | 1 | | 3 | 5 | 42 | | | | | | 19 | 53 | | |
| 9 | 75 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 12 | 33 | | |
| 3 | 25 | 1 | | 0 | | 0 | 1 | 8 | | | | | | 11 | 31 | | |
| 46 | | 6 | 2 | 1 | 2 | 6 | 17 | | 25 | 5 | 29 | 7 | 25 | 91 | | 7 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 72 | 30 | | 5 | | 30 | | 25 | 42 | | 48 | | 42 | | 45 | 58 | |
| | 2 | | | | | | | 7 | | | | | | | 5 | 4 | |
| 6 | 30 | 1 | 0 | 0 | 0 | 0 | 1 | 5 | 3 | | | | | 10 | 17 | | 149 |
| 0 | 0 | 0 | | 1 | | 0 | 1 | 8 | | | | | | 3 | 8 | | AR |
| 0 | 0 | 0 | | 1 | | 0 | 1 | 8 | | | | | | 1x | 3 | | |
| 0 | 0 | 0 | | 1 | | 0 | 1 | 8 | | | | | | 1x | 3 | | |
| 0 | 0 | 0 | | 1 | | 0 | 1 | 8 | | | | | | 1x | 3 | | |
| 6 | | 1 | 0 | 4 | 0 | 0 | 5 | | 3 | 3 | 6 | 0 | 4 | 16 | | 3 | |
| 68 | | | | | | | 68 | | x | | | | | 192 | | 12 | |
| | 9 | 5 | | 20 | | 0 | | 7 | 6 | | 10 | | 7 | | 8 | 25 | |
| | 9 | | | | | | | 9 | | | | | | | 9 | 7 | |
| 0 | 0 | 3 | 0 | 0 | 0 | 1 | 4 | 20 | 3 | | | | | 7 | 12 | | 149 |
| 0 | 0 | 0 | | 1 | | 1 | 2 | 17 | | | | | | 5x | 16 | | N |
| 0 | 0 | 1 | | 0 | | 1 | 2 | 17 | | | | | | 3x | 9 | | |
| 0 | 0 | 2 | | 0 | | 0 | 2 | 17 | | | | | | 2x | 6 | | |
| 0 | 0 | 2 | | 3 | | 1 | 6 | 50 | | | | | | 6x | 19 | | |
| 0 | | 8 | 0 | 4 | 0 | 4 | 16 | | 8 | 3 | 8 | 0 | 4 | 23 | | 3 | |
| 68 | | | | | | | 68 | | x | | | | | 188 | | 12 | |
| | 0 | 40 | | 20 | | 20 | | 24 | 18 | | 13 | | 7 | | 12 | 25 | |
| | 10 | | | | | | | 7 | | | | | | | 8 | 7 | |
| 18 | 90 | 3 | 0 | 1 | 0 | 0 | 4 | 20 | 5 | | | | | 23 | 38 | | 150 |
| 12 | 100 | 1 | | 0 | | 0 | 1 | 8 | | | | | | 15 | 42 | | AR |
| 9 | 75 | 4 | | 0 | | 0 | 4 | 33 | | | | | | 13 | 36 | | |
| 8 | 67 | 1 | | 0 | | 0 | 1 | 8 | | | | | | 9 | 25 | | |
| 5 | 42 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 5 | 14 | | |
| 52 | | 9 | 0 | 1 | 0 | 0 | 10 | | 26 | 5 | 17 | 4 | 13 | 65 | | 5 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 76 | 45 | | 5 | | 0 | | 15 | 43 | | 28 | | 22 | | 32 | 42 | |
| | 2 | | | | | | | 8 | | | | | | | 6 | 5 | |
| 16 | 80 | 2 | 0 | 0 | 0 | 0 | 2 | 10 | 4 | | | | | 18 | 30 | | 150 |
| 6 | 50 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 11 | 31 | | N |
| 6 | 42 | 0 | | 0 | | 2 | 2 | 17 | | | | | | 9 | 25 | | |
| 6 | 50 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 11 | 31 | | |
| 2 | 17 | 0 | | 0 | | 0 | 0 | 0 | | | | | | 5 | 14 | | |
| 35 | | 2 | 0 | 0 | 0 | 2 | 4 | | 13 | 4 | 12 | 4 | 21 | 54 | | 4 | |
| 68 | | | | | | | 68 | | | | | | | 204 | | 12 | |
| | 52 | 10 | | 0 | | 10 | | 6 | 22 | | 20 | | 35 | | 26 | 33 | |
| | 4 | | | | | | | 9 | | | | | | | 7 | 6 | |

Determination of Rank

| 31-40 | 41-50 | 51-60 | 61-70 | 71-80 | 81-90 | 91-100 | Range Subdivisions |
|---|---|---|---|---|---|---|---|
| 6 | 5 | 4 | 3 | 2 | 1 | 0 | Rank Numbers |

Table 13 . -SUMMARY O

| Steel No. | Failures | Welded and Tested at All Te | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1/4" | | | | 1/2" | | | | | |
| | | AR | | N | | AR | | N | | AR | |
| | | % | Rank | % | Rank | % | Rank | % | Rank | % | R |
| 139 | Plate | 98 | 0 | 46 | 5 | 96 | 0 | 74 | 2 | 57 | |
| | Bond & Weld | 2 | 9 | 1 | 9 | 3 | 9 | 9 | 9 | 1 | |
| | All | 100 | 1 | 47 | 6 | 99 | 1 | 83 | 2 | 58 | |
| 144 | Plate | 100 | 0 | 65 | 3 | 99 | 0 | 69 | 3 | 81 | |
| | Bond & Weld | 0 | 10 | 18 | 8 | 4 | 9 | 0 | 10 | 7 | |
| | All | 100 | 1 | 83 | 2 | 103 | 0 | 69 | 4 | 88 | |
| 146 | Plate | 25 | 7 | 3 | 9 | 46 | 5 | 28 | 7 | 57 | |
| | Bond & Weld | 27 | 7 | 19 | 8 | 43 | 5 | 38 | 6 | 16 | |
| | All | 52 | 5 | 22 | 8 | 89 | 2 | 66 | 4 | 73 | |
| 147 | Plate | 97 | 0 | 31 | 6 | 57 | 4 | 34 | 6 | 93 | |
| | Bond & Weld | 10 | 9 | 37 | 6 | 59 | 4 | 72 | 2 | 15 | |
| | All | 107 | 0 | 68 | 4 | 116 | 0 | 106 | 0 | 108 | |
| 149 | Plate | 96 | 0 | 83 | 1 | 72 | 2 | 57 | 4 | 66 | |
| | Bond & Weld | 9 | 9 | 13 | 8 | 9 | 9 | 0 | 10 | 7 | |
| | All | 105 | 0 | 96 | 1 | 81 | 2 | 57 | 5 | 73 | |
| 150 | Plate | 94 | 0 | 26 | 7 | 28 | 7 | 24 | 7 | 84 | |
| | Bond & Weld | 4 | 9 | 22 | 7 | 76 | 2 | 52 | 4 | 15 | |
| | All | 98 | 1 | 48 | 6 | 104 | 0 | 76 | 3 | 99 | |

Determination of Ra

| Range Subdivisions | 0-10 | 11-20 | 21-30 | 31-40 | 41-50 | 51-6 |
|---|---|---|---|---|---|---|
| Rank Number | 10 | 9 | 8 | 7 | 6 | 5 |



UNIV. OF MICH.

SUMMARY OF ALL FAILURES.

| at All Temperatures | | | | | | | | W & T at 70°F | | | | Steel No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3/4" | | | | All Sizes Combined | | | All Sizes Combined | | | | |
| | AR | | N | | AR | | N | | AR | | N | |
| | % | Rank | % | Rank | % | Rank | % | Rank | % | Rank | % | Rank | |
| | 57 | 4 | 53 | 4 | 84 | 1 | 57 | 4 | 67 | 3 | 58 | 4 | 139 |
| | 1 | 9 | 0 | 10 | 2 | 9 | 3 | 9 | 0 | 10 | 0 | 10 | |
| | 58 | 5 | 53 | 5 | 86 | 2 | 60 | 5 | 67 | 4 | 58 | 5 | |
| | 81 | 1 | 32 | 6 | 93 | 0 | 55 | 4 | 83 | 1 | 17 | 8 | 144 |
| | 7 | 9 | 3 | 9 | 4 | 9 | 7 | 9 | 8 | 9 | 8 | 9 | |
| | 88 | 2 | 35 | 7 | 97 | 1 | 62 | 4 | 91 | 1 | 25 | 8 | |
| | 57 | 4 | 45 | 5 | 43 | 5 | 25 | 7 | 8 | 9 | 8 | 9 | 146 |
| | 16 | 8 | 8 | 9 | 29 | 7 | 22 | 7 | 8 | 9 | 42 | 5 | |
| | 73 | 3 | 53 | 5 | 72 | 3 | 47 | 6 | 16 | 9 | 50 | 6 | |
| | 93 | 0 | 75 | 2 | 82 | 1 | 47 | 5 | 58 | 4 | 0 | 10 | 147 |
| | 15 | 8 | 25 | 7 | 28 | 7 | 45 | 5 | 50 | 5 | 58 | 4 | |
| | 108 | 0 | 100 | 1 | 110 | 0 | 92 | 1 | 108 | 0 | 58 | 5 | |
| | 66 | 3 | 56 | 4 | 77 | 2 | 64 | 3 | 50 | 5 | 0 | 10 | 149 |
| | 7 | 9 | 24 | 7 | 8 | 9 | 12 | 8 | 25 | 7 | 25 | 7 | |
| | 73 | 3 | 80 | 3 | 85 | 2 | 76 | 3 | 75 | 3 | 25 | 8 | |
| | 84 | 1 | 44 | 5 | 69 | 3 | 31 | 6 | 83 | 1 | 25 | 7 | 150 |
| | 15 | 8 | 6 | 9 | 32 | 6 | 26 | 7 | 42 | 5 | 33 | 6 | |
| | 99 | 1 | 50 | 6 | 101 | 0 | 57 | 5 | 125 | 0 | 58 | 5 | |

ion of Rank - (All Failures)

| | 51-60 | 61-70 | 71-80 | 81-90 | 91-100 | 101 & over | Range Rank |
|---|---|---|---|---|---|---|---|
| | 5 | 4 | 3 | 2 | 1 | 0 | |

Table 14 . - SUMMARY OF RATINGS AND WEIGHTED

| Steel Number | | | 139 | | | 144 | | | 145 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Basis of Rating | Weight Factor | Plate Size | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd Ran |
| **Steels Welded and Tested at All Tem** | | | | | | | | | | | |
| Angle at Maximum Load | 3 | 1/4" | 59x | 4 | 12 | 52 | 0 | 0 | 65 | 7 | 21 |
| Average angle for | 3 | 1/2" | 56x | 2 | 6 | 60 | 4 | 12 | 68 | 8 | 24 |
| all specimens tested | 3 | 3/4" | 63x | 6 | 18 | 54 | 1 | 3 | 64 | 6 | 18 |
| | 6 | All | 59.3x | 4 | 24 | 55.3 | 2 | 12 | 65.7 | 7 | 42 |
| Total Wtd. Rank | 15 | | | | 60 | | | 27 | | | 105 |
| Deviations Below 60° | 3 | 1/4" | 316x | 6 | 18 | 832 | 1 | 3 | 28 | 9 | 27 |
| of individual angles | 3 | 1/2" | 700x | 3 | 9 | 202 | 7 | 21 | 37 | 9 | 27 |
| at maximum load. | 3 | 3/4" | 129x | 8 | 24 | 567 | 4 | 12 | 13 | 9 | 27 |
| = 100Σ(60°-A)/N | 6 | All | 380x | 6 | 36 | 533 | 4 | 24 | 26 | 9 | 54 |
| Total Wtd. Rank | 15 | | | | 87 | | | 60 | | | 135 |
| Plate Failures | 2 | 1/4" | 98 | 0 | 0 | 100 | 0 | 0 | 25 | 7 | 14 |
| Percent of specimens | 2 | 1/2" | 96 | 0 | 0 | 99 | 0 | 0 | 42 | 5 | 10 |
| tested showing fail- | 2 | 3/4" | 57 | 4 | 8 | 81 | 1 | 2 | 57 | 4 | 8 |
| ures in plate metal. | 6 | All | 84 | 1 | 6 | 93 | 0 | 0 | 43 | 5 | 30 |
| Total Wtd.Rank | 12 | | | | 14 | | | 2 | | | 62 |
| All Failures - Percent | 1 | 1/4" | 100 | 1 | 1 | 100 | 1 | 1 | 52 | 5 | 5 |
| of specimens tested | 1 | 1/2" | 99 | 1 | 1 | 103 | 0 | 0 | 89 | 2 | 2 |
| showing failures in | 1 | 3/4" | 68 | 5 | 5 | 88 | 2 | 2 | 73 | 3 | 3 |
| plate, bond, or weld | 2 | All | 86 | 2 | 4 | 97 | 1 | 2 | 72 | 3 | 6 |
| Total Wtd. Rank | 5 | | | | 11 | | | 5 | | | 16 |
| Maximum Load | 1 | 1/4" | 3860 | 2 | 2 | 5400 | 10 | 10 | 4210 | 4 | 4 |
| Average for all | 1 | 1/2" | 6430 | 2 | 2 | 8120 | 8 | 8 | 7410 | 5 | 5 |
| specimens tested | 1 | 3/4" | 9880 | 5 | 5 | 10660 | 9 | 9 | 10690 | 9 | 9 |
| Total Wtd. Rank | 3 | | | | 9 | | | 27 | | | 18 |
| Total Weighted Rank | 10 | 1/4" | | | 33 | | | 14 | | | 71 |
| for all rating | 10 | 1/2" | | | 18 | | | 41 | | | 68 |
| factors combined. | 10 | 3/4" | | | 60 | | | 28 | | | 65 |
| | 20 | All | | | 70 | | | 38 | | | 132 |
| Total -All Sizes | 50 | | | | 181 | | | 121 | | | 336 |
| Relative Order No. (*) | | | | (5) | | | (6) | | | (1) | |
| **Steels Welded and Tested at 70°F (** | | | | | | | | | | | |
| Angle at Maximum Load | 3 | 1/4" | -- | 8* | 24 | 61 | 5 | 15 | 65 | 7 | 21 |
| | 3 | 1/2" | 70x | 9 | 27 | 56 | 2 | 6 | 75 | 10 | 30 |
| | 3 | 3/4" | 68 | 8 | 24 | 51 | 0 | 0 | 62 | 5 | 15 |
| | 6 | All | 69.0x | 9 | 54 | 56.0 | 2 | 12 | 67.3 | 8 | 48 |
| Deviations Below 60° | 3 | 1/4" | -- | 10* | 30 | 25 | 9 | 27 | 0 | 10 | 30 |
| | 3 | 1/2" | 0x | 10 | 30 | 500 | 5 | 15 | 0 | 10 | 30 |
| | 3 | 3/4" | 0 | 10 | 30 | 925 | 0 | 0 | 0 | 10 | 30 |
| | 6 | All | 0x | 10 | 60 | 483 | 5 | 30 | 0 | 10 | 60 |
| Plate Failures - % | 12 | All | 67 | 3 | 36 | 83 | 1 | 12 | 8 | 9 | 108 |
| All Failures | 5 | All | 67 | 4 | 20 | 91 | 1 | 5 | 16 | 9 | 45 |
| Maximum Load | 1 | 1/4" | 3755 | 1 | 1 | 5100 | 8 | 8 | 3968 | 2 | 2 |
| | 1 | 1/2" | 5810 | 0 | 0 | 7570 | 6 | 6 | 6962 | 4 | 4 |
| | 1 | 3/4" | 9450 | 3 | 3 | 10210 | 7 | 7 | 10300 | 7 | 7 |
| Total Weighted Rank | 50 | Total | | | 339 | | | 143 | | | 430 |
| Relative Order No. (*) | | | | (2) | | | (6) | | | (1) | |

D WEIGHTED RANKS - As Rolled Plates.

| 146 | | 147 | | | 149 | | | 150 | | | Ranges of Ratings | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Best | | Worst | |
| Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank | Rating | Rank |
| at All Temperatures -20°F to 70°F | | | | | | | | | | | | | | |
| 7 | 21 | 62 | 5 | 15 | 59x | 4 | 12 | 57 | 3 | 9 | 65 | 7 | 52 | 0 |
| 8 | 24 | 64 | 6 | 18 | 63 | 6 | 18 | 62 | 5 | 15 | 68 | 8 | 56x | 2 |
| 6 | 18 | 60 | 4 | 12 | 58 | 4 | 12 | 58 | 3 | 9 | 64 | 6 | 54 | 1 |
| 7 | 42 | 62.0 | 5 | 30 | 60.3 | 4 | 24 | 59.0 | 4 | 24 | 65.7 | 7 | 55.3 | 2 |
| | 105 | | | 75 | | | 66 | | | 57 | | | | |
| 9 | 27 | 50 | 9 | 27 | 284x | 7 | 21 | 457 | 5 | 15 | 28 | 9 | 832 | 1 |
| 9 | 27 | 134 | 8 | 24 | 197 | 8 | 24 | 209 | 7 | 21 | 37 | 9 | 700x | 3 |
| 9 | 27 | 213 | 7 | 21 | 291 | 7 | 21 | 347 | 6 | 18 | 13 | 9 | 567 | 4 |
| 9 | 54 | 132 | 8 | 48 | 256 | 7 | 42 | 338 | 6 | 36 | 26 | 9 | 533 | 4 |
| | 135 | | | 120 | | | 108 | | | 90 | | | | |
| 7 | 14 | 97 | 0 | 0 | 96x | 0 | 0 | 94 | 0 | 0 | 25 | 7 | 100 | 0 |
| 5 | 10 | 57 | 4 | 8 | 72 | 2 | 4 | 28 | 7 | 14 | 28 | 7 | 99 | 0 |
| 4 | 8 | 93 | 0 | 0 | 66 | 3 | 6 | 84 | 1 | 2 | 57 | 4 | 93 | 0 |
| 5 | 30 | 82 | 1 | 6 | 77 | 2 | 12 | 69 | 3 | 18 | 43 | 5 | 93 | 0 |
| | 62 | | | 14 | | | 22 | | | 34 | | | | |
| 5 | 5 | 107 | 0 | 0 | 105x | 0 | 0 | 98 | 1 | 1 | 52 | 5 | 107 | 0 |
| 2 | 2 | 116 | 0 | 0 | 81 | 2 | 2 | 104 | 0 | 0 | 81 | 2 | 116 | 0 |
| 3 | 3 | 108 | 0 | 0 | 73 | 3 | 3 | 99 | 1 | 1 | 58 | 5 | 108 | 0 |
| 3 | 6 | 110 | 0 | 0 | 85 | 2 | 4 | 101 | 0 | 0 | 72 | 3 | 110 | 0 |
| | 16 | | | 0 | | | 9 | | | 2 | | | | |
| 4 | 4 | 4430 | 5 | 5 | 4620x | 6 | 6 | 4550 | 5 | 5 | 5400 | 10 | 3860 | 2 |
| 5 | 5 | 7790 | 6 | 6 | 7490 | 5 | 5 | 7950 | 7 | 7 | 8120 | 8 | 6430 | 2 |
| 9 | 9 | 11150 | 10 | 10 | 10420 | 8 | 8 | 9500 | 3 | 3 | 11150 | 10 | 9500 | 3 |
| | 18 | | | 21 | | | 19 | | | 15 | | | | |
| | 71 | | | 47 | | | 39 | | | 30 | | 71 | | 14 |
| | 68 | | | 56 | | | 53 | | | 57 | | 68 | | 18 |
| | 65 | | | 43 | | | 50 | | | 33 | | 65 | | 28 |
| | 132 | | | 84 | | | 82 | | | 78 | | 132 | | 38 |
| | 336 | | | 230 | | | 224 | | | 198 | | 336 | | 121 |
| (1) | | | (2) | | | (3) | | | (4) | | | | | |
| d at 70°F (Room Temperature) only. | | | | | | | | | | | | | | |
| 7 | 21 | 60 | 4 | 12 | 60 | 4 | 12 | 60 | 4 | 12 | 65 | 7 | 60 | 4 |
| 10 | 30 | 73 | 10 | 30 | 69 | 9 | 27 | 68 | 8 | 24 | 75 | 10 | 56 | 2 |
| 5 | 15 | 63 | 6 | 18 | 67 | 8 | 24 | 50 | 0 | 0 | 68 | 8 | 50 | 0 |
| 8 | 48 | 65.3 | 7 | 42 | 65.3 | 7 | 42 | 59.3 | 4 | 24 | 69.0x | 9 | 56.0 | 2 |
| 10 | 30 | 50 | 9 | 27 | 150 | 8 | 24 | 175 | 8 | 24 | 0 | 10 | 175 | 8 |
| 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 500 | 5 |
| 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 1000 | 0 | 0 | 0 | 10 | 1000 | 0 |
| 10 | 60 | 17 | 9 | 54 | 50 | 9 | 54 | 392 | 6 | 36 | 0 | 10 | 483 | 5 |
| 9 | 108 | 58 | 4 | 48 | 50 | 5 | 60 | 83 | 1 | 12 | 8 | 9 | 83 | 1 |
| 9 | 45 | 108 | 0 | 0 | 75 | 3 | 15 | 125 | 0 | 0 | 16 | 9 | 125 | 0 |
| 2 | 2 | 4051 | 3 | 3 | 4745 | 6 | 6 | 4345 | 4 | 4 | 5100 | 8 | 3755 | 1 |
| 4 | 4 | 7150 | 4 | 4 | 7062 | 4 | 4 | 7850 | 7 | 7 | 7850 | 7 | 5810 | 0 |
| 7 | 7 | 10600 | 9 | 9 | 10100 | 6 | 6 | 8975 | 0 | 0 | 10600 | 9 | 8975 | 0 |
| | 430 | | | 307 | | | 334 | | | 173 | | 430 | | 143 |
| (1) | | | (4) | | | (3) | | | (5) | | | | | |

Table 15.- SUMMARY OF RATINGS AND WEIGHTED R

| Steel Number | | | 139 | | | 144 | | | 146 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Basis of Rating | Weight Factor | Plate Size | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wt Ra |
| **Steels Welded and Tested at All Te** | | | | | | | | | | | |
| Angle at Maximum Load | 3 | 1/4" | 66 | 7 | 21 | 61 | 5 | 15 | 66 | 7 | 2 |
| Average angle for | 3 | 1/2" | 65x | 7 | 21 | 66 | 7 | 21 | 68 | 8 | 2 |
| all specimens tested | 3 | 3/4" | 63 | 6 | 18 | 61 | 5 | 15 | 64 | 6 | 1 |
| | 6 | All | 64.7x | 6 | 36 | 62.7 | 5 | 30 | 66.0 | 7 | 1 |
| Total Wtd. Rank | 15 | | | | 96 | | | 81 | | | 10 |
| Deviations Below 60° | 3 | 1/4" | 4 | 9 | 27 | 172 | 8 | 24 | 37 | 9 | 2 |
| of individual angles | 3 | 1/2" | 257x | 7 | 21 | 40 | 9 | 27 | 52 | 9 | 2 |
| at maximum load | 3 | 3/4" | 158 | 8 | 24 | 110 | 8 | 24 | 17 | 9 | 2 |
| =100Σ(60°-A)/N | 6 | All | 135 | 8 | 48 | 107 | 8 | 48 | 35 | 9 | 1 |
| Total Wtd. Rank | 15 | | | | 120 | | | 123 | | | 1 |
| Plate Failures | 2 | 1/4" | 46 | 5 | 10 | 65 | 3 | 6 | 3 | 9 | 1 |
| Percent of specimens | 2 | 1/2" | 74 | 2 | 4 | 69 | 3 | 6 | 28 | 7 | 1 |
| tested showing fail- | 2 | 3/4" | 53 | 4 | 8 | 32 | 6 | 12 | 45 | 5 | 1 |
| ures in plate metal | 6 | All | 57 | 4 | 24 | 55 | 4 | 24 | 25 | 7 | 1 |
| Total Wtd. Rank | 12 | | | | 46 | | | 48 | | | 8 |
| All Failures - Percent | 1 | 1/4" | 47 | 6 | 6 | 83 | 2 | 2 | 22 | 8 | |
| of specimens tested | 1 | 1/2" | 83 | 2 | 2 | 69 | 4 | 4 | 66 | 4 | |
| showing failures in | 1 | 3/4" | 53 | 5 | 5 | 35 | 7 | 7 | 53 | 5 | |
| plate, bond, or weld | 2 | All | 60 | 5 | 10 | 62 | 4 | 8 | 47 | 6 | 1 |
| Total Wtd. Rank | 5 | | | | 23 | | | 21 | | | 2 |
| Maximum Load | 1 | 1/4" | 3840 | 2 | 2 | 4670 | 6 | 6 | 3840 | 2 | |
| Average for all | 1 | 1/2" | 6430 | 2 | 2 | 7700 | 6 | 6 | 7250 | 5 | |
| specimens tested | 1 | 3/4" | 9580 | 3 | 3 | 9230 | 2 | 2 | 10310 | 7 | |
| Total Wtd. Rank | 3 | | | | 7 | | | 14 | | | 1 |
| Total Weighted Rank | 10 | 1/4" | | | 66 | | | 53 | | | 1 |
| for all rating | 10 | 1/2" | | | 50 | | | 54 | | | 7 |
| Factors combined | 10 | 3/4" | | | 58 | | | 60 | | | 6 |
| | 20 | All | | | 118 | | | 110 | | | 15 |
| Total - All Sizes | 50 | | | | 292 | | | 287 | | | 36 |
| Relative Order No. (*) | | | | (4) | | | (5) | | | (1) | |
| **Steels Welded and Tested at 70°F** | | | | | | | | | | | |
| Angle at Maximum Load | 3 | 1/4" | 65 | 7 | 21 | 72 | 10 | 30 | 61 | 5 | 1 |
| | 3 | 1/2" | 68 | 8 | 24 | 68 | 8 | 24 | 67 | 8 | 2 |
| | 3 | 3/4" | 66 | 7 | 21 | 64 | 6 | 18 | 66 | 7 | 2 |
| | 6 | All | 66.3 | 7 | 42 | 68.0 | 8 | 48 | 64.7 | 6 | 1 |
| Deviations Below 60° | 3 | 1/4" | 0 | 10 | 30 | 0 | 10 | 30 | 500 | 5 | 1 |
| | 3 | 1/2" | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 3 |
| | 3 | 3/4" | 0 | 10 | 30 | 25 | 9 | 27 | 0 | 10 | 3 |
| | 6 | All | 0 | 10 | 60 | 8 | 9 | 54 | 167 | 8 | 4 |
| Plate Failures | 12 | All | 58 | 4 | 48 | 17 | 8 | 96 | 8 | 9 | 10 |
| All Failures | 5 | All | 58 | 5 | 25 | 25 | 8 | 40 | 50 | 6 | 3 |
| Maximum Load | 1 | 1/4" | 3687 | 1 | 1 | 4685 | 6 | 6 | 3603 | 0 | |
| | 1 | 1/2" | 6162 | 1 | 1 | 7655 | 6 | 6 | 6825 | 3 | |
| | 1 | 3/4" | 9088 | 1 | 1 | 8962 | 0 | 0 | 9738 | 4 | |
| Total Weighted Rank | 50 | Total | | | 334 | | | 409 | | | 36 |
| Relative Order No. (*) | | | | (6) | | | (2) | | | (5) | |



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WEIGHTED RANKS- Normalized Plates.

| | 146 | | 147 | | | 149 | | | 150 | | | Ranges of Ratings | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Best | | Worst | |
| g | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank No. | Wtd. Rank | Rating | Rank | Rating | Rank |
| d at All Temperatures -20°F to 70°F | | | | | | | | | | | | | | | |
| | 7 | 21 | 64 | 6 | 18 | 58x | 3 | 9 | 62 | 5 | 15 | 66 | 7 | 58x | 3 |
| | 8 | 24 | 68 | 8 | 24 | 64 | 6 | 18 | 64 | 6 | 18 | 68 | 8 | 64 | 6 |
| | 6 | 18 | 62 | 5 | 15 | 60 | 4 | 12 | 62 | 5 | 15 | 64 | 6 | 60 | 4 |
| 0 | 7 | 42 | 64.7 | 6 | 35 | 60.7 | 4 | 24 | 62.7 | 5 | 30 | 66.0 | 7 | 60.7 | 4 |
| | | 105 | | | 93 | | | 63 | | | 78 | | | | |
| | 9 | 27 | 35 | 9 | 27 | 442x | 5 | 15 | 209 | 7 | 21 | 4 | 9 | 442x | 5 |
| | 9 | 27 | 24 | 9 | 27 | 209 | 7 | 21 | 194 | 8 | 24 | 24 | 9 | 257 | 7 |
| | 9 | 27 | 70 | 9 | 27 | 193 | 8 | 24 | 110 | 8 | 24 | 17 | 9 | 193 | 8 |
| | 9 | 54 | 43 | 9 | 54 | 268 | 7 | 42 | 171 | 8 | 48 | 35 | 9 | 268 | 7 |
| | | 135 | | | 135 | | | 102 | | | 117 | | | | |
| | 9 | 18 | 31 | 6 | 12 | 83x | 1 | 2 | 26 | 7 | 14 | 3 | 9 | 83x | 1 |
| | 7 | 14 | 34 | 6 | 12 | 57 | 4 | 8 | 24 | 7 | 14 | 24 | 7 | 74 | 2 |
| | 5 | 10 | 75 | 2 | 4 | 56 | 4 | 8 | 44 | 5 | [illegible] | 32 | 6 | 75 | 2 |
| | 7 | 42 | 47 | 5 | 30 | 64x | 3 | 18 | 31 | 6 | 36 | 25 | 7 | 64 | 3 |
| | | 84 | | | 58 | | | 36 | | | 74 | | | | |
| | 8 | 8 | 68 | 4 | 4 | 96x | 1 | 1 | 48 | 6 | 6 | 28 | 8 | 96x | 1 |
| | 4 | 4 | 106 | 0 | 0 | 57 | 5 | 5 | 76 | 3 | 3 | 57 | 5 | 106 | 0 |
| | 5 | 5 | 100 | 1 | 1 | 80 | 3 | 3 | 50 | 6 | 6 | 35 | 7 | 100 | 1 |
| | 6 | 12 | 92 | 1 | 2 | 76 | 3 | 6 | 57 | 5 | 10 | 47 | 6 | 92 | 1 |
| | | 29 | | | 7 | | | 15 | | | 25 | | | | |
| | 2 | 2 | 4070 | 3 | 3 | 4610x | 6 | 6 | 3840 | 2 | 2 | 4670 | 6 | 3840 | 2 |
| | 5 | 5 | 7560 | 6 | 6 | 7260 | 5 | 5 | 7300 | 5 | 5 | 7700 | 6 | 6430 | 2 |
| | 7 | 7 | 10680 | 9 | 9 | 10230 | 7 | 7 | 9170 | 1 | 1 | 10680 | 9 | 9170 | 1 |
| | | 14 | | | 18 | | | 18 | | | 8 | | | | |
| | | 76 | | | 64 | | | 33 | | | 58 | | 76 | | 33 |
| | | 74 | | | 69 | | | 57 | | | 64 | | 74 | | 50 |
| | | 67 | | | 56 | | | 54 | | | 56 | | 67 | | 54 |
| | | 150 | | | 122 | | | 90 | | | 124 | | 150 | | 90 |
| | | 367 | | | 311 | | | 234 | | | 302 | | 367 | | 234 |
| | (1) | | | (2) | | | (6) | | | (3) | | | | | |
| ed at 70°F (Room Temperature) only. | | | | | | | | | | | | | | | |
| | 5 | 15 | 62 | 5 | 15 | 68 | 8 | 24 | 69 | 9 | 27 | 72 | 10 | 61 | 5 |
| | 8 | 24 | 69 | 9 | 27 | 69 | 9 | 27 | 68 | 8 | 24 | 69 | 9 | 67 | 8 |
| | 7 | 21 | 63 | 6 | 18 | 66 | 7 | 21 | 66 | 7 | 21 | 66 | 7 | 63 | 6 |
| 7 | 6 | 36 | 64.7 | 6 | 36 | 67.7 | 8 | 48 | 67.7 | 8 | 48 | 68.0 | 8 | 64.7 | 6 |
| | 5 | 15 | 200 | 8 | 34 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 500 | 5 |
| | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 0 | 10 |
| | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 30 | 0 | 10 | 25 | 9 |
| | 8 | 48 | 67 | 9 | 54 | 0 | 10 | 60 | 0 | 10 | 60 | 0 | 10 | 167 | 8 |
| | 9 | 108 | 0 | 10 | 120 | 0 | 10 | 120 | 25 | 7 | 84 | 0 | 10 | 58 | 4 |
| | 6 | 30 | 58 | 5 | 25 | 25 | 8 | 40 | 58 | 5 | 25 | 25 | 8 | 58 | 5 |
| | 0 | 0 | 3808 | 2 | 2 | 4360 | 4 | 4 | 3860 | 2 | 2 | 4685 | 6 | 3603 | 0 |
| | 3 | 3 | 7288 | 5 | 5 | 6750 | 3 | 3 | 7112 | 4 | 4 | 7655 | 6 | 6162 | 1 |
| | 4 | 4 | 10050 | 6 | 6 | 10050 | 6 | 6 | 8962 | 0 | 0 | 10050 | 6 | 8962 | 0 |
| | (5) | 364 | | (3) | 392 | | (1) | 443 | | (4) | 385 | | 443 | | 334 |

on the range of values found for each size, afford an approximate basis for comparison.

To determine the rank numbers, the total range of the property under consideration was divided into 11 subdivisions, which were given consecutive rank numbers from 0 to 10. A rank of 0 was assigned to the subdivision at the least desirable end of the range and a rank of 10 to that in the most desirable end of the range of values. High rank numbers then indicate the best steels, as judged on the basis of this particular property. The rank numbers also afford a means for comparing the effect of testing conditions, such as temperature of welding and testing, plate thickness, and heat treatment, since all of the rank numbers for any property were based on the same table of range subdivisions, except in the case of maximum load (table 8), in which different ranges were used for the different plate thicknesses.

These rank numbers for a particular property are used to indicate, by small numbers, which are easily compared, the relative merit of the steels under different conditions. These rank numbers are used also in the determination of the weighted rank (tables 14, 15, and 16), in which several rating factors are considered.

The maximum load usually increased with increase in thickness of the plate. The maximum loads for the normalized steels were generally lower than for the specimens of corresponding steels in the as-rolled condition.

The data of table 8 are shown graphically in figure 9, in which the average loads of each of the three thicknesses of plates are shown by means of the lengths of their respective bars.

Figures 10 and 11 show, respectively, the variation of maximum load with testing temperature and with the temperature at which the specimens were welded. The three groups of curves in each column represent the three plate sizes, ¾, ½, and ¼ in., reading from top to bottom. The data given in figure 9 are also shown in these figures by the double circles in the left of each column. The small "x" indicates that the data are incomplete for these points.

These two figures indicate that the maximum load increased as the temperature of testing was reduced from room temperature to −20° F, but that the relation between maximum load and the temperatures at which the specimens were welded was entirely random and independent of the testing temperature.

### 2. ANGLE AT MAXIMUM LOAD

The angles at maximum loads for each of the six steels under different conditions of welding and testing are given in table 9. The values are the average angles for four duplicate specimens tested under the same conditions. In each of the large boxes under the respective plate-size headings, the average angles for the respective welding temperatures indicated in the top box are read horizontally, and the variation with testing temperature, given in the second column of the table, is read vertically. The value in the upper left-hand corner of each box represents the average angle for the four specimens welded and tested at room temperature. The average angle for

431173—42——2

all specimens of one size and condition (normally 68) in the 17 combinations of welding and testing temperatures is given in the lower right-hand corner of each box. The relative rank of the steels is indicated in the columns headed "rank"; the rank for the room-temperature tests is found at the top of each small box, and that for

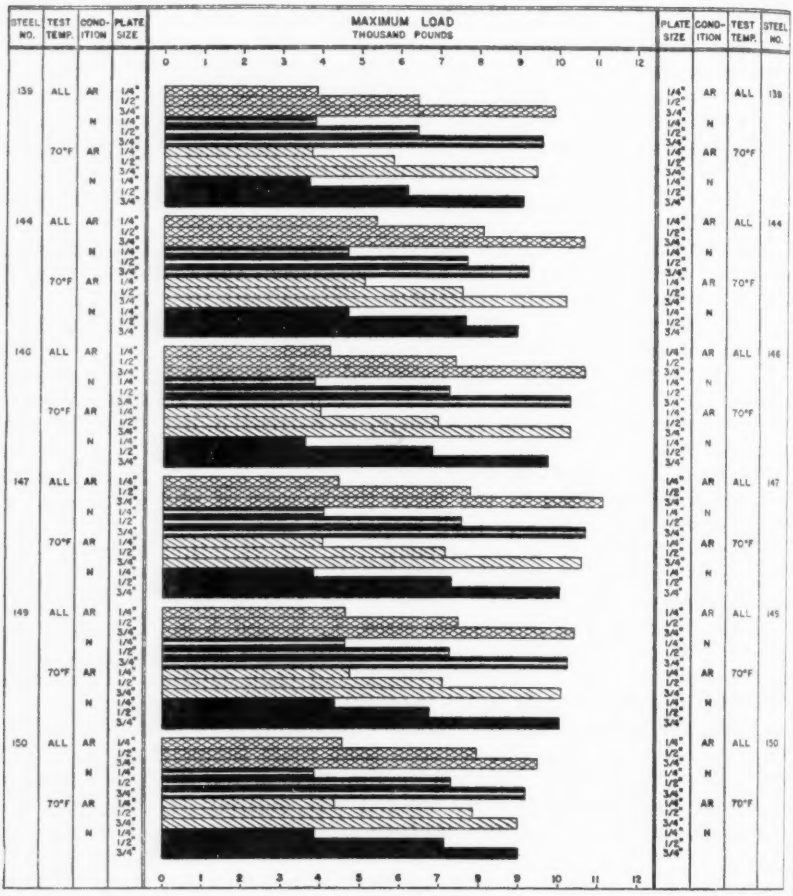


FIGURE 9.—*Maximum loads.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plates, welded and tested at 70° F.

the average of all combinations of welding and testing temperatures, at the bottom of the box.

The average angle and the rank for the three plate sizes combined are given in two columns at the right of the table, for the specimens welded and tested at room temperature (70° F) and for the average of all temperature combinations.

The principal data of table 9 are shown graphically in figure 12.

For specimens welded and tested at 70° F, the bending angles for all thicknesses were approximately the same for the as-rolled and normalized conditions. One outstanding exception was steel 144, in which the angles were considerably greater for the normalized condition than for the as-rolled condition. From tensile and microscopic studies it was believed that when rolled this steel had been finished

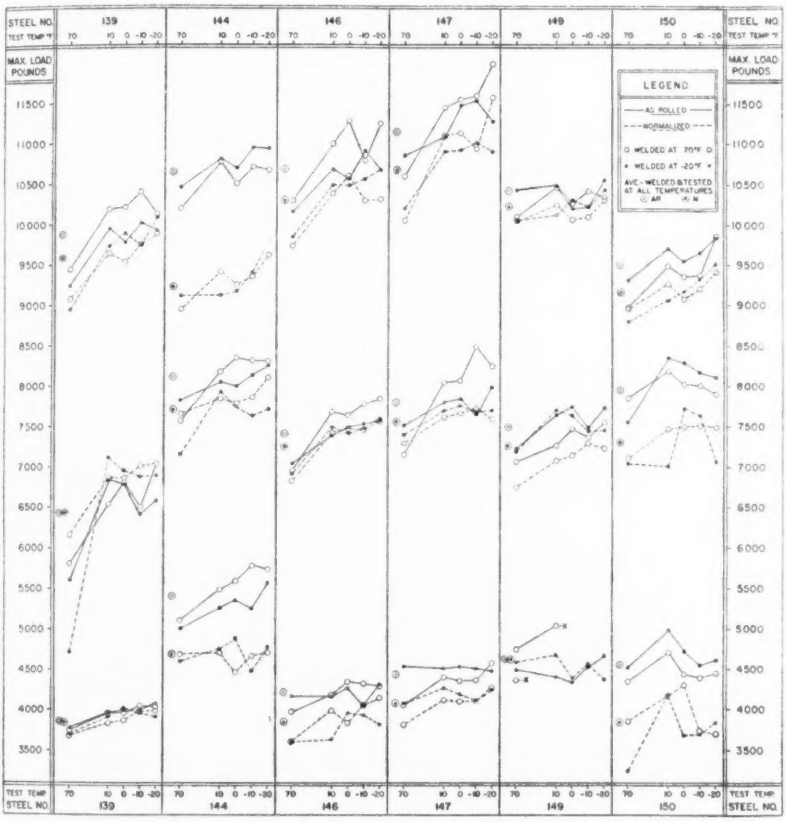


FIGURE 10.—*Relation of maximum loads to testing temperatures.*

"cold." This apparently contributed to the great differences in bending angles in the two conditions. The different sizes of plates were rolled from different heats of steel.

The ¼-in. plates of steel 149 and the ¼- and ¾-in. plates of steel 150 likewise bent to greater angles in the normalized condition than in the as-rolled. The plates were rolled from different heats.

Steels 139, 146, and 147 had uniform bending angles in the as-rolled and normalized conditions.

The variation in angle at maximum load with testing temperature is shown in figure 13, in which are plotted results of tests of speci-

mens welded at 70° F and at −20° F in both the as-rolled and the normalized conditions and tested at different temperatures. These results show that the trend is toward lower angles at lower testing temperatures. This tendency is less marked in steels 139, 146, and 147 than in the others, indicating that testing temperatures have less influence on the angles at maximum load in these steels than on the other three.

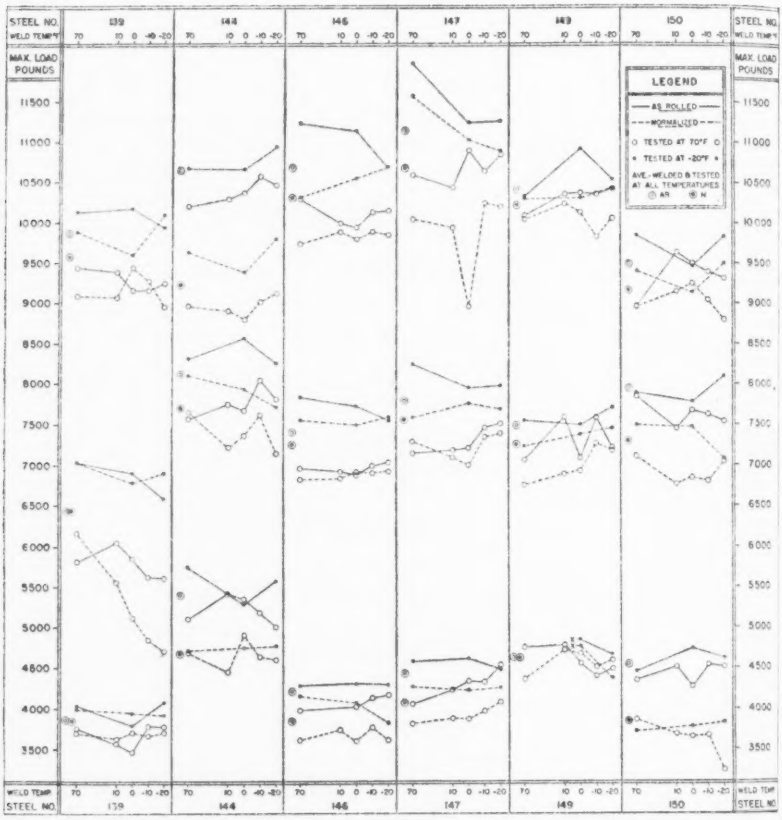


FIGURE 11.—*Relation of maximum loads to welding temperatures.*

The variation in angle at maximum load with welding temperatures is shown in figure 14, in which are plotted results of tests of steels welded at various temperatures and tested at 70° and −20° F in both the as-rolled and the normalized conditions. These results show that there is a slight tendency toward lower bending angles at lower welding temperatures, although the trend is not well marked. In general, low testing temperatures appeared to have more effect on bending angles at maximum load than the temperature of the plates before welding.

In the use of any statistical method of analysis for interpretation of data, some precaution must be taken to insure credit being given to the material which is uniform in properties as compared with one which

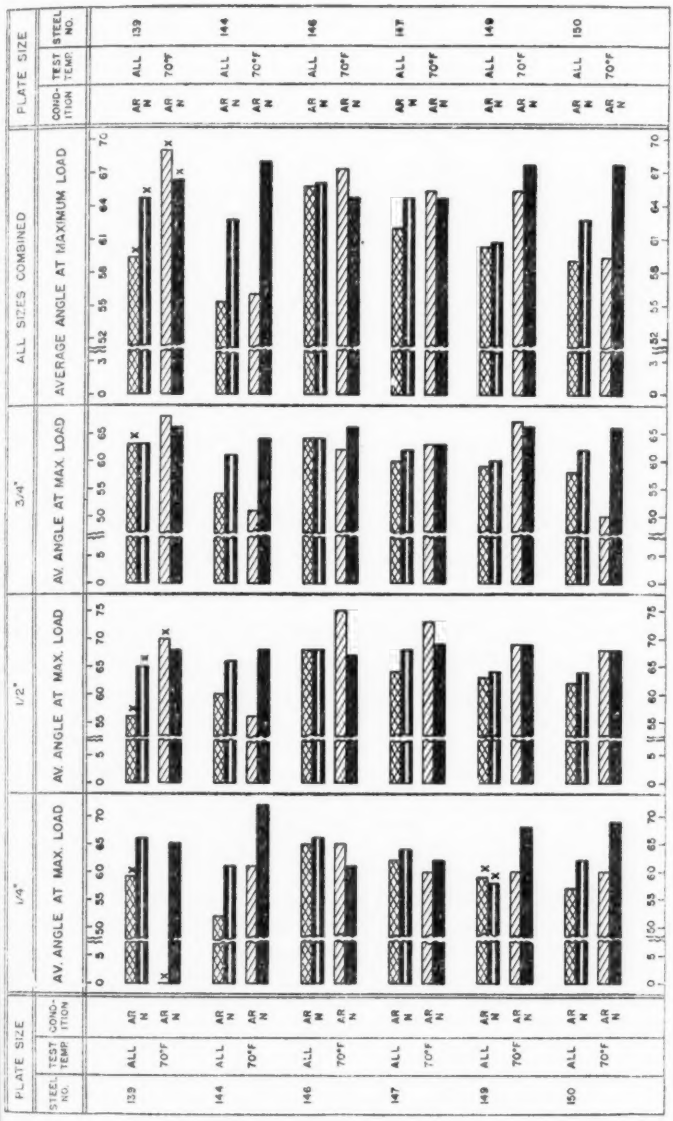


FIGURE 12.—*Angle of bend at maximum load.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plates, welded and tested at 70° F.

may have a high average for properties, but scatter considerably between the extremes. For this reason, a system was devised which would penalize in a final rating any lack of uniformity in angles at

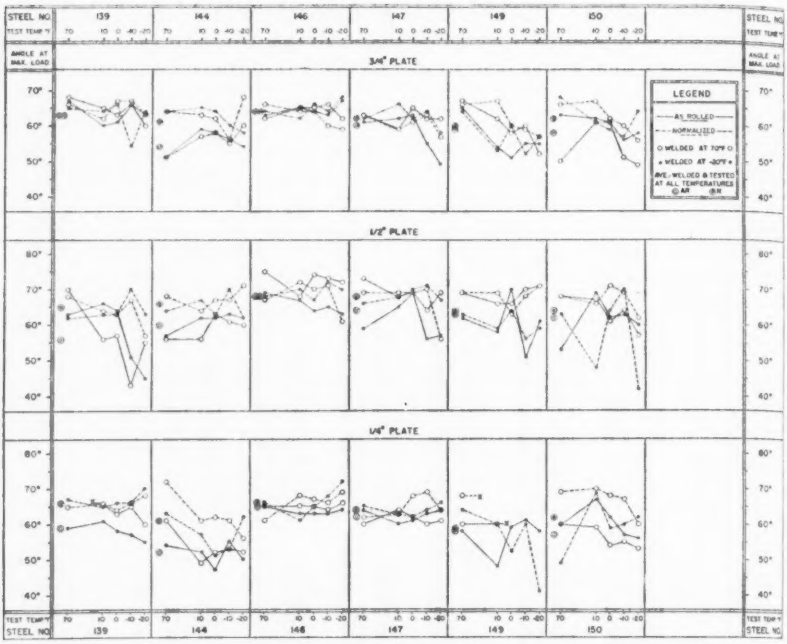


FIGURE 13.—*Relation of angle at maximum load to testing temperatures.*

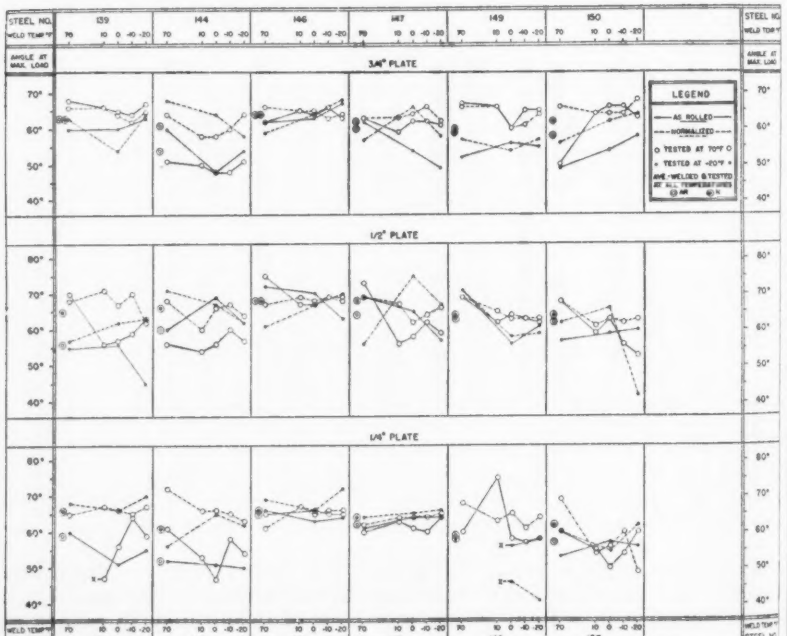


FIGURE 14.—*Relation of angle at maximum load to welding temperatures.*

maximum load for duplicate specimens in each group, although the average angle of a group might have been high. The deviations in angles are given in table 10. The values in the large boxes are the sums of the deviations below 60° of the angles for the individual specimens, tested at the combinations of welding and testing temperatures indicated respectively in the heading and the second column of the table. That is, if, for an individual specimen, the angle at maximum load is less than 60°, the difference, or 60° minus the angle, is taken as the deviation; if the angle is 60° or more, it is disregarded, since the interest is only in those specimens which show a low angle. The angle 60° was chosen arbitrarily as a value high enough to include any significantly low measurements of the angle, but not so high as to include average or above-average values, since if all of the angles showed a negative deviation from the reference angle, the average of these deviations would merely be another way of stating the average angle.

The figures in the large boxes of the table then represent the sum of these negative deviations for the four specimens tested at each temperature combination; if less than four specimens were tested, the figure appears as a fraction, the denominator representing the number of specimens. In the lower right-hand corner of each box the total deviation for all specimens is shown as the numerator of a fraction, the denominator representing the total number of specimens.

The rating is this fraction multiplied by 100—expressed mathematically, the rating is $100\Sigma(60°-A)/N$, where $A$ is the angle at maximum load for each individual specimen in which this angle is less than 60° and $N$ is the total number of specimens. The rating and the rank for the specimens welded and tested at room temperature are shown in the top part of the smaller boxes; and for the average of all temperature combinations in the lower part of these boxes. The rank is determined from the range of ratings by reference to the tabulation at the bottom of the table, as outlined in the discussion of table 8. It should be noted in this case that a high rating of deviations is undesirable; hence the rank numbers are assigned in reverse order, so that steels with low deviations have high rank numbers. The data of this table are shown graphically in figure 15, in which the length of the bars is proportional to the average deviation below 60° of the individual maximum load angles for the test groups indicated in the columns at the left. A long bar, indicating a large average deviation below 60°, may mean that the average angle is low; but if the average angle, as shown in figure 12, is above 60°, the deviations or scatter of the individual measurements are large. Either of these conditions is undesirable from the viewpoint of reliability of the weld as indicated by the angle at maximum load, so that in this figure a *short* bar indicates a steel with reasonably consistent bending angles and with an average angle above 60°.

### 3. FAILURES

Failures in the bend test occurred in three locations: (1) in the plate metal; (2) in the bond zone; and (3) in the weld metal. Failures in the plate metal were considered the least desirable. Table 11 lists

the number of failures in the plate metal and table 12 in the bond zone and weld metal.

If both a plate failure and a bond or weld failure were observed in the same specimen, both failures were recorded in the respective tables.

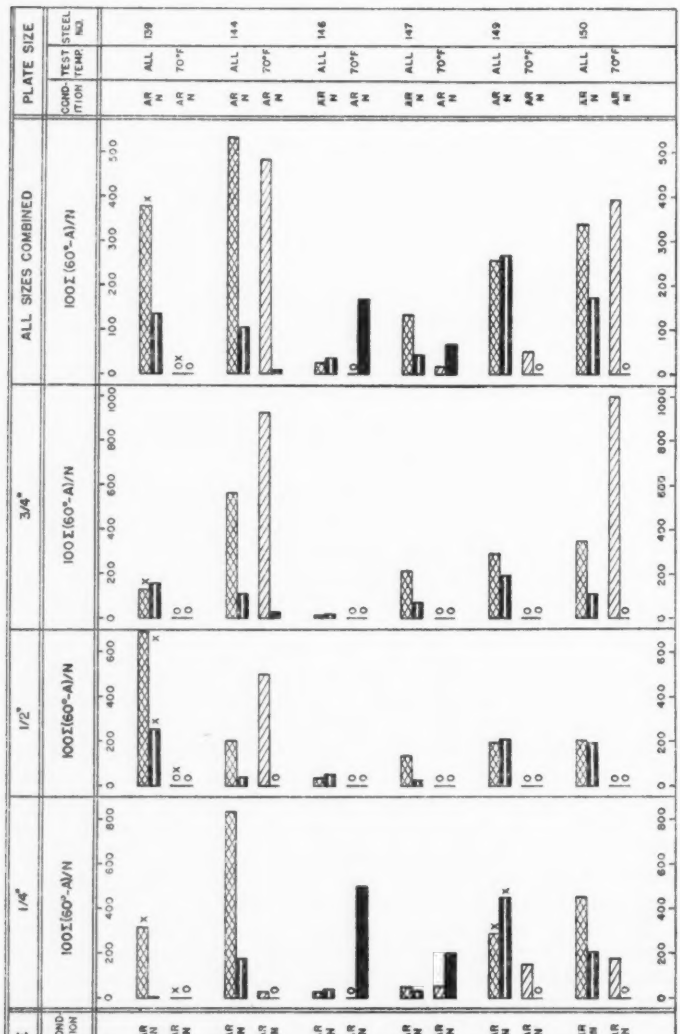


FIGURE 15.—*Deviations below 60° of individual angles at maximum load.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plate, welded and tested at 70°F.

The figures in the upper part of the large boxes represent the number of specimens which failed under the test conditions indicated in the column heads and the columns at the left. Four specimens were tested for each set of conditions, unless otherwise indicated by a fraction.

in which the numerator represents the number of specimens which failed, and the denominator the number tested. The figures at the bottom of each box represent the percentage of failures for the entire groups of specimens welded at a given temperature and tested at all temperatures. The percentage values in the columns to the right of the boxes indicate the percentage of failures in the group of specimens tested at the given temperature but welded at different temperatures. At the bottom of these columns is the percentage of failures in the entire group, welded and tested at all temperature combinations, followed by the rank determined from the tabulation at the bottom of the sheet. The data for "all sizes combined" are obtained by cross-addition of the corresponding totals for each of the three sizes. The last column gives, for the specimens welded and tested at room temperature, the data indicated by the subheads in the first column, for all sizes combined.

Table 13 summarizes the results given in tables 11 and 12. The total is greater than 100 percent in several instances, because several of the specimens showed both types of failure, which were tabulated separately in tables 11 and 12. The data in table 13 are shown graphically in figure 16, and the variations in percentage of failures with testing and welding temperatures are shown in figures 17 and 18.

The percentage of plate failures is highest in the ¼-in. thicknesses and lowest in the ½-in. thicknesses in the as-rolled condition. In normalized plates, the percentage of plate failures increases as the plate thickness increases, being lowest in the ¼-in. plates and highest in the ¾-in. plates. There were fewer plate failures in the normalized condition than in the as-rolled condition.

Usually bond or weld failures did not occur when there was an early plate failure; therefore if there were many plate failures, there were few bond or weld failures. Probably for this reason the average percentage of bond and weld failures in ¼- and ¾-in. thicknesses was higher in the normalized than in the as-rolled condition.

In the as-rolled plates, the percentage of bond and weld failures was low in the ¼- and ¾-in. thicknesses and relatively high in the ½-in. thicknesses. In the normalized condition there were fewer bond and weld failures in the ¾-in. than in the ½-in. thicknesses.

All failures, including both plate and bond or weld failures were highest in the ½-in. thicknesses both as-rolled and normalized. Normalized plates, in general, had fewer failures of all types than as-rolled plates, in all thicknesses.

The number of plate failures increased, in almost every case, as the testing temperature was decreased. This increase was slightly more pronounced in the normalized than in the as-rolled condition.

The relation between plate failures and temperatures at which the plates were welded is not so pronounced as the relation to testing temperatures, but there was a slight increase in number of plate failures for specimens welded at lower temperatures.

The relationship of bond and weld failures to the welding and testing temperatures is overshadowed by the increase in plate failures at the lower temperatures. This has a decided effect on the number of bond or weld failures.

There is no indication, from these results, of any critical region of either welding or testing temperature, in the range 70° to −20° F., at which there was a sudden increase in the number of failures.

Considering all sizes combined and the averages of all combinations of welding and testing temperatures, steel 146 had the smallest number of plate failures and of all failures combined, in both the as-rolled and the normalized conditions. Plate failures were greatest in steel 144 in the as-rolled condition and in steel 149 in the normalized condition. Total failures were highest in steel 147 in both the as-rolled and normalized conditions, although most of these failures were in the bonds or welds.

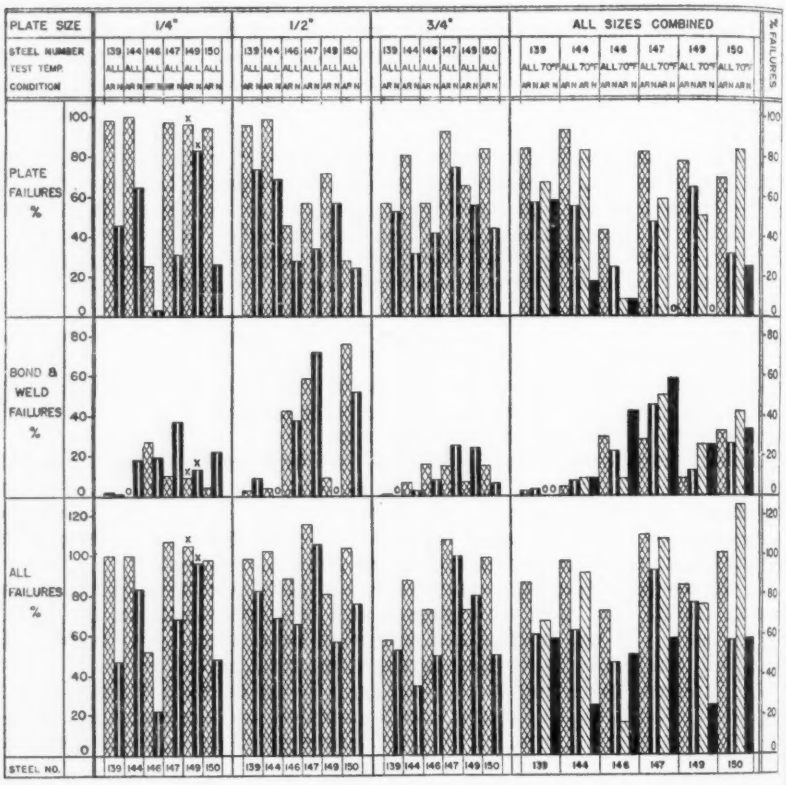


FIGURE 16.—*Failures of specimens.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plates, welded and tested at 70° F.

The relative merit of each steel as determined by the percentage of plate failures and the relation of plate failures to chemical, hardness, and tensile properties for each size separately will be considered in a later section.

Fractures in the T-bend specimens were classified as follows:

*Type I.* A crack which started in the bond zone at the toe of the fillet and followed the fusion zone under the weld, but did not turn into the plate metal.

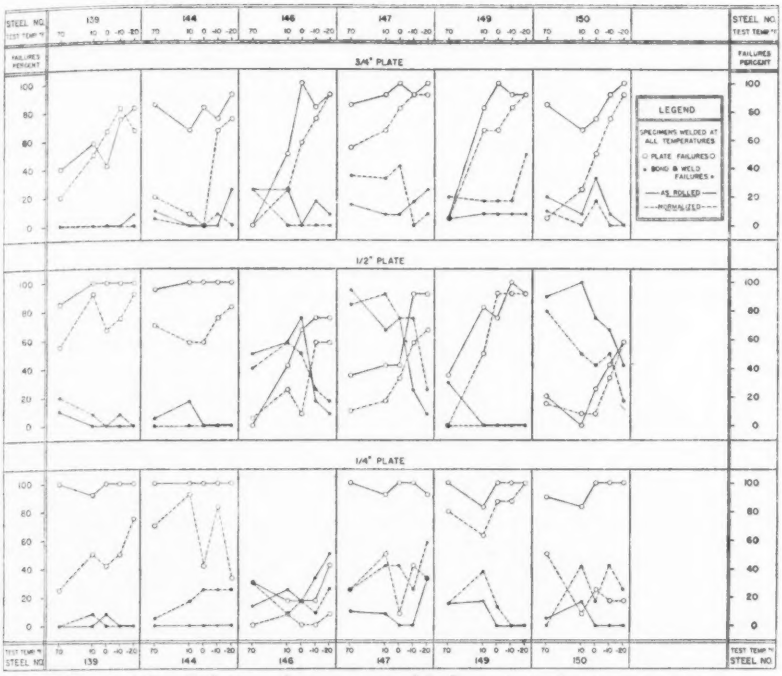


FIGURE 17.—*Relation of percentage of failures to testing temperatures.*

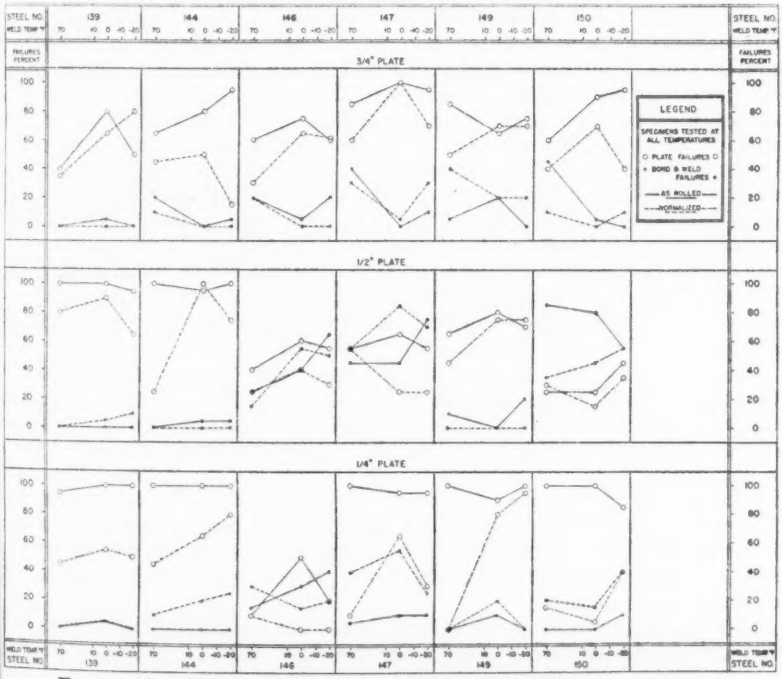


FIGURE 18.—*Relation of percentage of failures to welding temperatures.*

*Type II.* A crack which started at the toe of the fillet and extended either directly into the plate metal or followed the fusion zone for a short distance and then turned into the plate. This type of fracture progressed gradually without sudden or sharp rupture of the plate metal.

*Type III.* A sudden or sharp crack which generally started at the toe of the fillet and extended into the plate.

Typical fractures are shown in figures 19 and 20. Figure 19 (*A*) shows a specimen which did not fail but bent to the capacity of the jig. Figure 19 (*B*, *C*, and *D*) show type I fractures which extended along the fusion zone but did not turn into the plate. Figure 19 (*E*) is a composite fracture which started as a type I fracture, tearing both fillets from the plate, then turned into the plate and became a type II fracture. Figure 19 (*F*) is a type II fracture which started as type I and then extended gradually into the plate, fracturing it completely on one side and almost completely on the other side. Figure 20 (*G* and *H*) are type III fractures. Figure 20 (*G*) also contained a weld fracture which started in a blowhole. Figure 20 (*I*) is a type III fracture which broke through the plate suddenly and completely with a sharp report. Figure 20 (*J*, *K*, and *L*) are failures which are occasionally found in laminated plates. The plate shown in Figure 20 (*K*) separated completely at a large lamination without transverse fracture of either plate or weld metals. The T-member shown in Figure 20 (*L*) contained a lamination which separated without failure of plate or weld metals.

## V. DISCUSSION

Because of the large number of specimens and the number of different conditions under which the tests were conducted, a statistical method of evaluation of the data was deemed desirable. The number of specimens tested under each condition was small, only four. The rating method was based on a consideration of all of the conditions rather than on a large number of results from any one given condition. Several factors were either measured or noted during the investigation, and these were believed to have contributed to the welding quality of a steel to different extents. The final weighted rating then had to contain a consideration of all contributing factors.

During the course of investigation, several steels were eliminated from further consideration because of early failures or because of some other factor. These steels are not considered in the rating charts given below, but are discussed in section VI.

In tables 14 and 15 are summarized, for the as-rolled and the normalized conditions, respectively, the ratings and rank numbers derived in the preceding tables from the various measurements and observations of the T-bend tests. The weighted rank calculated from a combination of the various rating factors is also given. The data in the upper part of each table are the averages of the 17 test groups for all combinations of welding and testing temperatures. In the lower part of the tables, the data represent the single test groups of four specimens for each plate thickness, which were welded and tested at room temperature.

The second column in each table gives the weighting factor assigned to each basis of rating shown in the first column. These weights

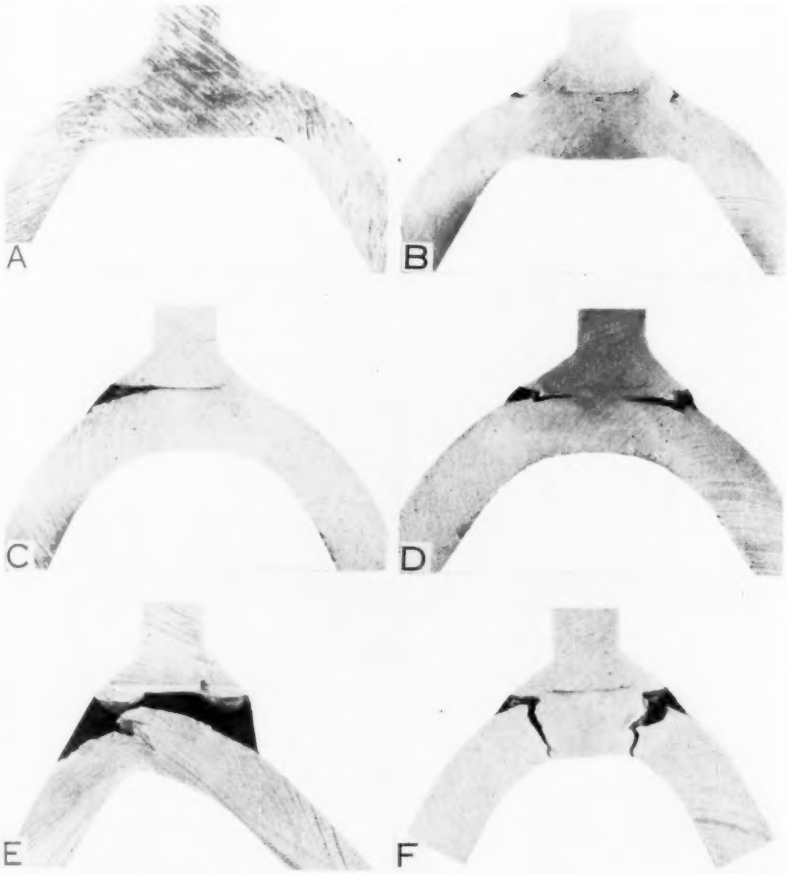


FIGURE 19.—*Typical fractures of T-bend specimens.*

*A*, No failure. *B*, Slight bond failure, both sides; type I fracture. *C*, Complete bond failure, following line of fusion; type I fracture. *D*, Bond failure, complete; gradual failure along heat-affected zone; type I fracture. *E*, Bond failure, complete, both sides; plate failure, two-thirds, originating in bond; types I and II fractures. *F*, Plate failure, complete, both sides; started as bond failures, then turned into plate; type II fracture.

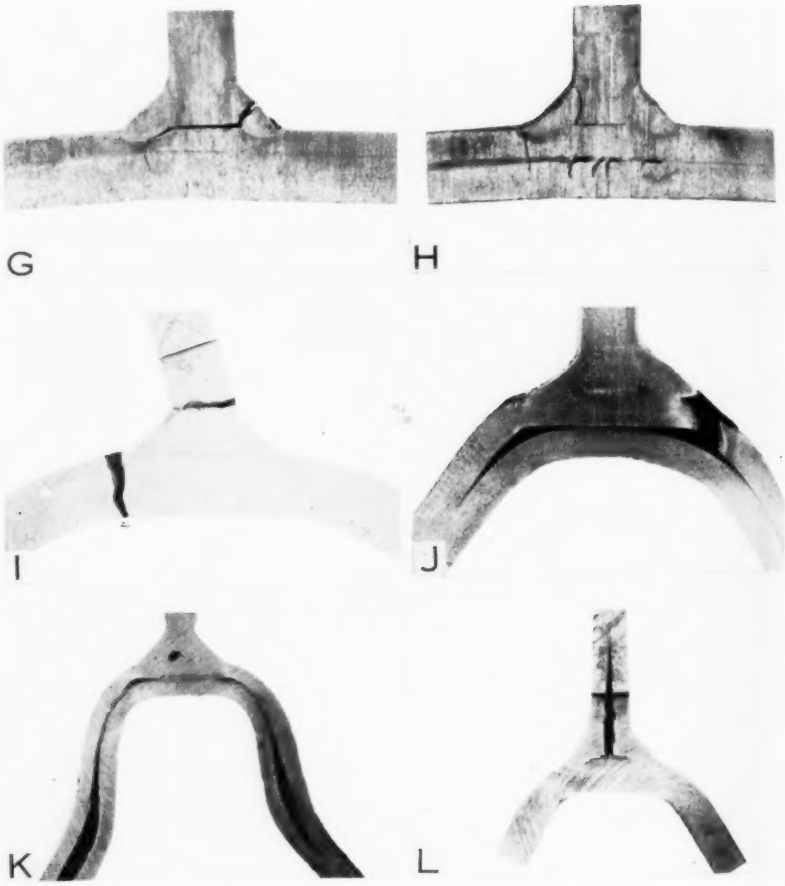


FIGURE 20.—*Typical fractures of* T*-bend specimens.*

*G*, Weld failure, complete through blowhole; plate failure, two-thirds, sharp under opposite fillet; type III fracture. *H*, Plate failure, one-half, sharp; bond failure complete along tongue of specimen; type III fracture. *I*, Plate failure, complete, sharp; tongue broken by impact at failure of plate; type III fracture. *J*, Plate failure, one-half, laminated plate, failed by separation of laminations. *K*, Laminated plate, failed by separation and buckling without transverse cracking. *L*, Stresses relieved by opening of lamination in tongue; no failure in plate metal, bond zone, or weld metal.

were adjusted so that the sum of the weighting factors for each plate size would equal 10, allowing a maximum possible weighted rank of 100, since the highest rank number is also 10. The sum of the weighting factors for all sizes combined was made equal to 50, by assigning appropriate weights to the averages of the various ratings for all thicknesses of each steel.

The largest weight was given to the ratings based on the angle at maximum load, which is the most accurate of the measurements in the T-bend tests, and probably the most significant, since any kind of failure at a small angle of deflection resulted in a low angle at maximum load. Two ratings are based on this measurement: (1) the average angle, and (2) the average deviation below 60° of the angle measurements for individual specimens. This latter rating assigns a lower rank to steels for which the angle at maximum load was below 60° for any individual specimen, thus penalizing nonuniformity as well as a low average angle.

The percentage of plate failures was given less weight, because the angle of deflection at failure is a factor which was not considered. This angle was recorded in most of the tests, but it could not be determined accurately in the low-temperature tests, where the specimen was immersed in liquid; and even in the tests at room temperature the determination of the exact beginning of the failure, which was often very gradual, depended largely on the opinion of the observer. At times the beginning of the failure could not be observed, particularly if it started at the back of the specimen on the side opposite to the observer.

Failures in the bond or weld metal were not considered separately in this determination of the weighted rank, because they do not depend entirely on the character of the plate metal. These failures appeared to be more or less of a residual type, that is, specimens which did not fail in the plate metal often failed in the bond or weld at high angles of deflection. However, a failure in the bond or weld relieved internal stresses in the specimen, and thereby tended to reduce the probability of a plate failure. Therefore, the rating on all failures, which includes both plate failures and bond or weld failures, was given a small weight in the determination of weighted rank.

The smallest weight was given to the rating based on the measurement of maximum load. A high maximum-load rating would appear to be desirable for welded structures, but frequently a high load rating was associated with a low angle at maximum load in brittle steels, resulting in sharp, complete failures of the plate metal. The maximum-load measurements are not particularly significant, except for comparing specimens cut from the same plate, since this load is approximately a function of the cross-section area of metal at the joint, which could not be measured accurately because of slight variations in size and shape of the weld fillets. This effect cannot be evaluated by ordinary or simple measurements. For these reasons, the rating based on the maximum load was given only a small weight, and was included mainly for the purpose of making the summary complete, rather than for its effect on the total weighted rank.

In the body of each table (14 and 15), the first two columns under each steel number in the heading show the rating and the rank number for each of the rating factors, taken from the preceding tables. The

weighted rank in the third column is obtained by multiplying the rank number by the weight assigned in the second column of the table.

The numbers in parentheses at the bottom of each section of the table give the relative order of merit of the six steels, as determined by the total weighted rank for all thicknesses combined.

A summary at the right of each table gives the highest and the lowest values of the several ratings and rank numbers of each steel.

The method of determination of the weighted rank can perhaps be best explained by taking one steel as an example and following it through each of the steps necessary to determine the weighted rank.

Steel 139, as-rolled, is the example used. The summary of ratings and the rank numbers for this steel, and the weighted rank determined from these rank numbers, are found in the fourth, fifth, and sixth columns in the upper portion of table 14. The fourth column gives for each basis of rating indicated in the first column the rating for each size and in most cases for all sizes combined. The fifth column gives the rank number associated with each rating. The rating and rank numbers are taken from tables 8, 9, 10, 11, and 13. The sixth column gives the weighted ranks as obtained by multiplying the rank numbers by the weighting factor shown in the second column of table 14.

The first basis of rating considered is the average angle at maximum load, for all specimens tested in each plate thickness and including all combinations of welding and testing temperatures. The ratings and rank numbers for angles of bend at maximum load are found in table 9. The average angle at maximum load for all combinations of welding and testing temperatures (abbreviated: "av. all temperatures" in table 9) of ¼-in. thicknesses of steel 139 AR was 59°. From the section for determination of rank at the bottom of table 9, it is found that an angle of 59° corresponds to a rank number 4. Similarly, for the ½- and ¾-in. thicknesses with angles of 56° and 63°, respectively, the rank numbers are 2 and 6. For all sizes combined, specimens welded and tested at all temperatures (the column at the right of table 9,) the average angle is 59.3° and the rank number, 4.

In table 14, the weighted ranks (column 6) for the ¼-, ½- and ¾-in. thicknesses are found to be 12, 6, and 18, respectively. These were found by multiplying the respective rank numbers (determined as explained above in table 9) for each thickness by the weight factor 3. For all thicknesses combined, the rank number 4 is multiplied by the weighting factor 6, yielding 24 as the weighted rank. The sum of these four weighted ranks is 60, which may be compared with the values 27, 105, 75, etc. derived in a similar manner for the other steels.

The rating and rank numbers for deviations of individual angles below 60° are found in table 10. The rating numbers in this table represent the total of all deviations of angle of bend below 60° for the individual specimens, divided by the total number of specimens. These rating numbers were multiplied by 100 to eliminate decimals. It will be noted that although the data for steel 139 are incomplete, this rating is in the form of an average for the specimens tested and the rating would not be affected except insofar as the average of the missing specimens might differ from the average of the specimens tested. The weighted rank for deviations was obtained in the same manner as that for average angle.

The percentage of plate failures is given in table 11, and the rank numbers were taken from the tabulation at the bottom of this table. A summary of plate failures and rank numbers is given also in table 13. For plate failures, a weighting factor of 2 was used for each thickness and of 6 for all thicknesses combined.

The ratings for all failures in table 13 were obtained by adding the percentages of plate failures and of bond or weld failures. The rank numbers for all failures were determined from the tabulation of range subdivisions at the bottom of this table. A weight of 1 was used for calculation of the weighted rank for each thickness and a weight of 2 for all thicknesses combined.

For maximum load, the values in the "rating" (fourth) column represent the average maximum load, in pounds, of all specimens (in all combinations of welding and testing temperatures). These averages are given in table 8, and the rank numbers were obtained (separately for each thickness of plate) from the summary at the bottom of this table. A weight of 1 was assigned to the maximum load for each thickness; and since the average maximum load of all sizes combined has no particular significance, no rating was given in this case.

In the last section of the upper portion of table 14 are given the total weighted ranks for each thickness, for all thicknesses combined, and for the grand total. The total for each thickness is found by adding the weighted ranks for each of the five rating factors. For example, for the ¼-in. thickness of steel 139, the weighted ranks are: 12 for the angle, 18 for deviations, 0 for plate failures, 1 for all failures, and 2 for maximum load—a total of 33. This value may be used to compare the various thicknesses of the same steel or to compare different steels. For example, the ¼-in. thickness of steel 139 has a higher weighted rank, 33, than that of the ½-in. thickness, 18, but not so high as that of the ¾-in. thickness, 60. Therefore, the ¾-in. plate may be considered to have a better welding quality than either the ¼- or ½-in. plates and the ¼-in. plate to have a better welding quality than the ½-in. plate. Similarly, comparing the ¼-in. plates of different steels, it will be seen that steel 146 with a weighted rank of 71 and steel 144 with a weighted rank of 14 represent the extremes of the steels tested and that the welding quality decreases from steel 146, the most weldable, to steel 144, the least weldable.

The grand total (181 for steel 139) is the sum of the total weighted ranks for each of the three plate sizes and for all plates sizes combined, and is also the sum of the total weighted ranks for the five rating factors.

The value "(5)" at the bottom of the "rank" (fifth) column indicates that steel 139 was fifth in relative order of the six steels in the as-rolled condition under all combinations of welding and testing temperatures.

The weighted rank for tests at room temperature only, shown in the lower part of table 14, was calculated in a similar manner. The rating values for specimens welded and tested at room temperature are found in the tables indicated above, and the rank numbers were determined in the same manner.

Only four specimens of each plate thickness were tested at room temperature, and since this number is too small for the percentage

to be significant, the ratings for plate failures and for all failures were calculated for all thicknesses combined. In these two cases, the weighting factor was adjusted so that the weighted rank for all thicknesses combined in the tests at room temperature may be compared with the total weighted ranks for plate failures and for total failures, respectively, in tests under all temperature conditions.

The data for the angle at maximum load in the room-temperature tests of the ¼-in. thickness of steel 139, as-rolled, are missing. To complete the calculation of the weighted rank, a rank number equal to the lowest rank number for the other two thicknesses was arbitrarily assigned for the angle and for the deviation, which is dependent upon the individual angles. These rank numbers are indicated by stars.

For the three other factors, the rating, rank, and weighted rank for each thickness in the tests at room temperature may be compared directly with the corresponding values for tests under all temperature combinations. Such a comparison shows that, for each of the weighting factors considered, steel 139, as-rolled, shows to better advantage at room temperature than in the low-temperature tests.

This method of analysis of data was devised to compare the welding qualities of the various steels. The steels may be directly compared by means of any one of the five rating factors, by any combination of them, or by all of them taken together, depending upon which factors may be considered to be the most important in the conduct of a test.

The summaries of the ratings and the weighted rank given in tables 14 and 15 are shown graphically in figure 21. The left half of the chart shows the weighted rank of all thicknesses combined, for each steel in the as-rolled and the normalized conditions, and for the tests at room temperature as well as at all combinations of welding and testing temperatures. The right half of the chart shows the weighted rating for each plate thickness, in both as-rolled and normalized conditions. These ratings are for the average of tests at all combinations of welding and testing temperatures. Tests made at room temperature only are not considered for each thickness separately, because only a small number of specimens was tested.

The several components of the weighted rating are indicated by different shadings of the bars, and the relative weight assigned to each factor is shown in the legend at the bottom of the chart.

In table 14, the upper portion is devoted to welds made and tested at all temperatures while the lower portion contains results of tests of steels welded and tested at room temperature only. For steels welded and tested at all temperatures, the values, last line, for total weighted rank range from 121, for steel 144, to 336 for steel 146. For steels welded and tested at room temperature only, the total values range from 143, for steel 144, to 430 for steel 146.

The values for all steels are higher under room-temperature conditions than under lower temperature conditions except for steel 150, which was slightly lower in the room-temperature tests. This indicates that welding and testing at low temperatures caused a decrease in the bending properties of welded steels. Steel 150, which contained approximately 2 percent of nickel, might be expected to have good bending properties at low temperatures because of the well-known beneficial effect of nickel on the physical properties at subnormal temperatures. However, other steels also contained nickel in about the same amount, and these had decidedly lower bending properties

at low temperatures than at room temperature. Closer examination of the data for the individual thicknesses of steel 150 indicates, however, that for the ¼- and ½-in. plates, the average angles were higher and the deviations below 60° were lower at room temperature than at

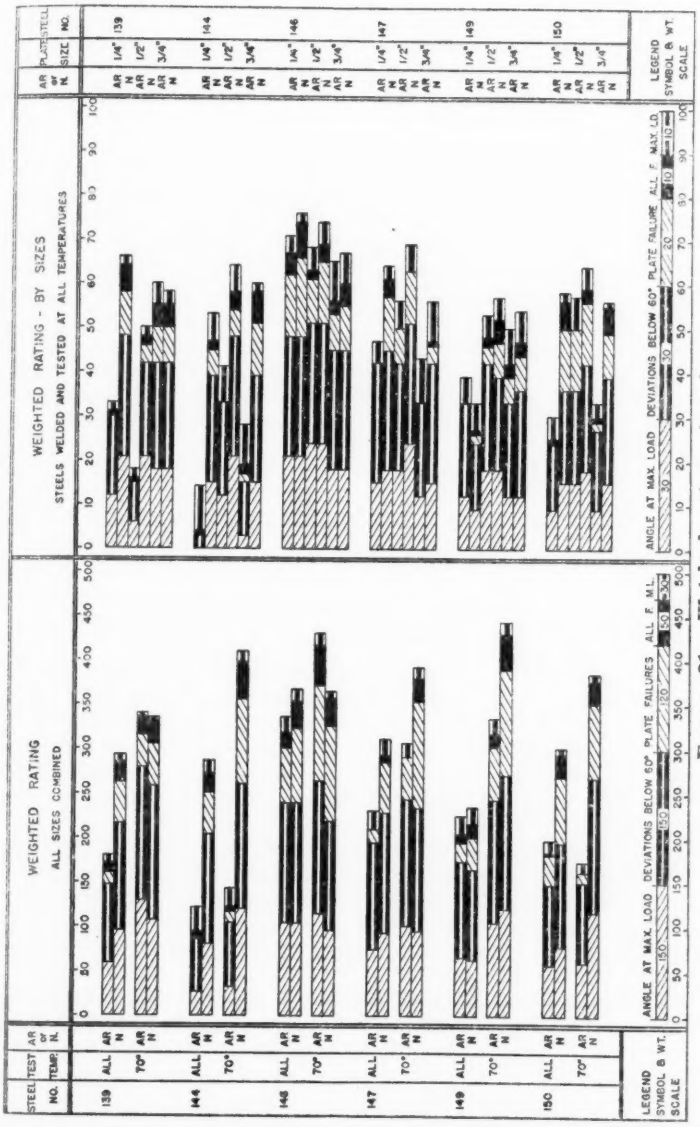


FIGURE 21.—*Weighted ratings of steels.*

lower temperatures. Calculation of the weighted rank for the individual thicknesses in the tests at room temperature (not shown in the table) showed that in the ¾- and the ¼-in. thicknesses, the weighted ranks for tests at room temperature were higher than for tests at all

temperature combinations. For the ¾-in. thicknesses, however, the weighted rank was much lower, and this thickness alone lowered the weighted rank of all sizes combined, in the tests at room temperature. The low rank for the ¾-in. specimens tested at room temperature was due to the extremely low angles at maximum load. One specimen containing a plate lamination failed at an angle of 35°, and the angle at maximum load for the other three specimens ranged from 52° to 57°, an average of 50° for the four specimens tested. There was a wide and erratic variation of the angles at maximum load for specimens of this steel tested at other combinations of welding and testing temperatures, as shown in table 9 and in figures 13 and 14. The low rating of the ¾-in. specimens of steel 150 in tests at room temperature was due to nonuniformity of this steel, which has been discussed previously.

The relative order of total weighted rank (small numbers in parentheses, last line of both upper and lower portions of table 14) differed considerably for tests made at room temperature and for those made at all temperatures. Based on these order numbers, steel 146 ranked first and steel 144 last (sixth) in both cases. However, steel 139, which had order number 2 in room-temperature tests, was fifth in tests under all temperature conditions, while steels 147 and 150 had lower order numbers in tests at all temperatures than at room temperature.

Steel 146 had a total weighted rank of 430 when welded and tested at room temperature and 336 at all temperatures. Only steel 139 welded and tested at room temperature had a higher total weighted rank than steel 146 at all temperatures.

Results for the specimens from normalized plates welded and tested in all temperature conditions (table 15 and fig. 21) indicated that the total weighted rank for all sizes combined was higher in every case than for the same steel in the as-rolled condition. The weighted rank for steel 149 in the normalized condition was only slightly greater than in the as-rolled plates, with the result that relative order number of this steel dropped from 3 in the as-rolled condition to 6 in the normalized. Except for this difference, the relative order numbers of all steels were the same in the normalized condition as in the as-rolled condition for tests at all combinations of welding and testing temperatures.

A comparison of results of tests at room temperature with those at all temperature combinations, for normalized steels, shows that with the exception of steel 146, all steels had lower weighted ranks in tests at all combinations of welding and testing temperatures than at room temperature only. Steel 146 had practically the same value in both cases.

In the normalized condition, steel 149 was first in relative order for material welded and tested at room temperature only but was last for tests at all temperature combinations of welding and testing. This indicates that the bending properties of this steel were adversely affected by both welding and testing at low temperatures. Reference to figures 13, 14, 17, and 18 indicates that the lower number for this steel at all combinations of welding and testing temperatures was due mostly to the behavior at the low testing temperatures, although in the ½-in. thicknesses there was a definite decrease in the angle at maximum load and an increase of plate failures, at low welding tem-

peratures. There may be some relation between low order numbers for this steel at low testing temperatures and the unusually small improvement of welding properties on normalizing. There was nothing unusual in the tensile or hardness properties, or in the changes of these properties on normalizing, to indicate that the change of welding quality on normalizing should be different than for the other steels. The tensile properties at low temperatures were not measured. It may be significant that this steel was the only one containing a large amount of phosphorus.

A comparison of the ratings in the as-rolled and the normalized conditions for tests at room temperature only (tables 14 and 15 and fig. 21) indicates that steels 139 and 146 had lower weighted ranks in the normalized condition. The weighted ranks for all other steels were higher in the normalized conditions than in the as-rolled conditions, much higher in steels 144 and 150. Since the ratings of the normalized steels welded and tested at room temperature were all comparatively high and cover only a limited range, the relative order is not of particular significance.

The lower rating of normalized steel 146, in room-temperature tests, is due in large part to the low rating of the ¼-in. thickness, caused by a bond failure of one of the four specimens at an angle of 40°. Since this steel was quite uniform, the low angle for this specimen was probably due to a weld defect.

The rating for the tests at room temperature for steel 139, as-rolled, may be too high, because some of the data were incomplete and the method of computing the angles was changed after the first few tests.

The ratings for steel 144, as-rolled, were consistently much lower than the ratings for the normalized condition. This obtained for all thicknesses and for tests made at low temperatures as well as at room temperature. This steel had considerably lower yield point and tensile strength in the normalized than in the as-rolled condition, indicating a considerable amount of rolling hardening. It would appear, therefore, that the considerably larger weighted rank for steel 144 normalized was due to actual improvement of welding quality by the normalizing treatment. This steel had many manganese sulfide inclusions and was the "dirtiest" of the six steels.

The low rating of steel 150, as-rolled, in room temperature tests has been attributed, previously, to nonuniformity of the steel. In the normalized condition, the angles at maximum load were considerably higher and more uniform than in the as-rolled condition, indicating that the plates were made more weldable by the normalizing treatment.

The relative order of the steels in each thickness and condition and the total weighted ratings of the different thicknesses and conditions of treatment for each steel are shown more clearly in the upper part of figure 22. The left half of the chart shows the comparative ratings of the various sizes of each steel for the as-rolled and the normalized conditions, and on the right half is shown the effect of normalizing the plates before welding. In each column of the chart, the steel numbers are shown opposite the respective ratings for the size and condition indicated in the column heads, and lines are drawn to connect the corresponding steel numbers in each of the columns which are to be compared. The average for the six steels is given in each column, and these average values are connected by dotted lines.

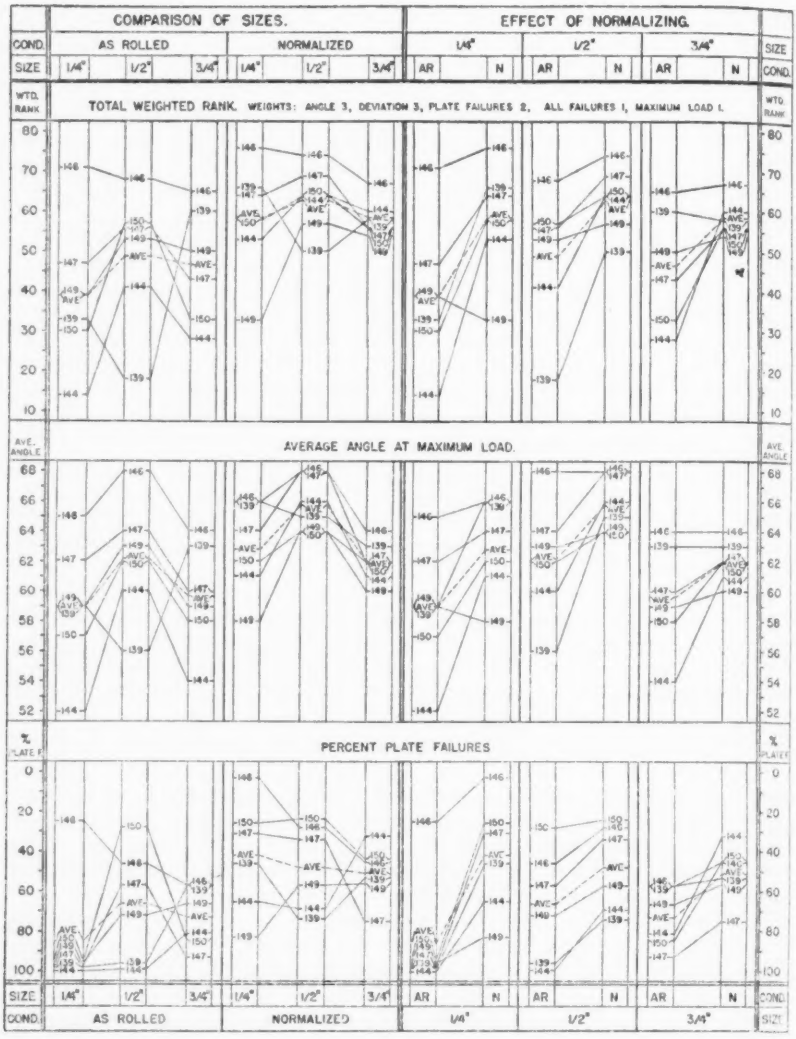


FIGURE 22.—*Comparison of ratings and methods of weighting.*

Steels welded and tested at all temperatures.

The comparisons between the different thicknesses of plates show that for most of the steels the highest ratings were found in the ½-in. thicknesses, in both the as-rolled and the normalized conditions.

An attempt was made to find a relation between the ratings for each thickness of each steel and the depth of heat penetration in the plate. The maximum penetration was measured on macrographs of the specimens welded at room temperature. There was no correlation

between the maximum heat penetration and the ratings for tests made at any temperature.

The effect of normalizing as measured by the weighted rank is shown in the right half of figure 22. In all cases except two, the weighted rank for the normalized plates of one size of a steel is higher than for the as-rolled plates. It is noted also that steels having the lowest weighted ranks in the as-rolled condition showed the greatest improvement after the normalizing treatment. The ¾-in. plates of steel 139 and the ¼-in. plates of steel 149 are two exceptions which have a decrease of weighted rank after normalizing. The ½- and ¾-in. plates of steel 149 increased less in rating after normalizing than the average for the other steels. The fact that for each size of this steel the improvement of weighted rating on normalized plates was less than for the other steels tested (one thickness actually showed a decrease) substantiates the finding, previously discussed, that the average rating for all sizes combined showed a very low increase on normalizing, and indicates that this was inherent in the steel itself and was not a function of size or an accidental fluctuation. From table 2, it is noted that the physical properties of this steel were very similar in both the as-rolled and normalized conditions, indicating that this steel may have been normalized at the mill prior to shipment.

The normalized ¾-in. plates of steel 139 had lower ratings than the as-rolled plates, while the normalized ¼- and ½-in. plates had considerably higher ratings. This would indicate that the behavior of the ¾-in. plates was abnormal.

Figure 22 also shows the ratings of the steels, based on the average angle at maximum load and on the percentage of plate failures. The scale for the rating on the basis of percentage of plate failures is reversed, so that the steels in which there were few plate failures appear near the tops of the columns. These ratings serve as a check on the validity of the ratings based on the weighted rank. The relative order of the steels (reading from top to bottom in the columns) and the curves indicating the changes of rating with size and with normalizing are about the same in all sections of the figure. A study of the curves and of the relative order of the steels shows that, while the ratings based on the average angle at maximum load and on the percentage of plate failures, respectively, do not agree in every detail, there is substantial evidence that a close relation exists between the angle at maximum load and the number of plate failures.

Plate failures had more effect on the angles at maximum load than bond or weld failures because: first, bond failures were residual failures which usually occurred at angles greater than the normal angle at maximum load; and, second, the cross section of the specimen was not reduced to any great extent, although the reinforcing effect of the weld fillet was partially eliminated.

The ratings based on the weighted rank are weighted averages of all of the measurements obtained in the tests. The weights, shown in the heading of the upper section of figure 22, were arbitrarily assigned for reasons previously discussed. Since the largest weights were given to the angle at maximum load and to the deviations below 60°, the ratings based on the weighted rank should agree closely with the ratings based on this angle. This is evident in the two upper sections

of figure 22. Differences may be explained as the effect of the plate failures on the weighted rating, as shown in the lower section of the figure. The other factors in the weighted rating, namely, all failures (including plate failures and bond failures), and maximum load, were given small weights, and their effect on the weighted rank is almost negligible, as can be seen by comparing the three methods of rating shown in figure 22.

A brief summary, using the order numbers, which is based on all five factors and all thicknesses, is given in table 16.

TABLE 16.—*Order numbers of welded steels*

| Order number | Steel number | | | |
|---|---|---|---|---|
| | As-rolled | | Normalized | |
| | Room temperature | All temperatures | Room temperature | All temperatures |
| 1 | 146 | 146 | 149 | 146 |
| 2 | 139 | 147 | 144 | 147 |
| 3 | 149 | 149 | 147 | 150 |
| 4 | 147 | 150 | 150 | 139 |
| 5 | 150 | 139 | 146 | 144 |
| 6 | 144 | 144 | 139 | 149 |

Steel 146 was first for all conditions except when welded and tested in the normalized condition at room temperature, where its order was fifth. However, a further analysis indicated that values of total weighted rank of this steel did not decrease under these conditions, but were approximately the same. However, the welding quality of other steels, notably 144, was appreciably improved if the plates were welded in the normalized condition. It would appear therefore that the welding quality of steel 144 was appreciably influenced by normalizing. Evidence of this is shown in figures 23 and 24, photographs of ½-in. plates welded and tested at room temperature in the as-rolled and normalized conditions, respectively. When tested in the as-rolled condition, all specimens failed in the plate metal (four type III fractures), with sharp reports. The average angle at maximum load was 56°. Specimens from the plate normalized before welding bent to the limit of the jig without failure and with an average angle of 68°.

Summarizing, for all tests the order was as follows: 146, 147, 149, 150, 139, 144.

To determine whether changing the method of weighting would appreciably affect the relative order of these steels, other methods of weighting are compared in table 17, together with a summary of the weighted rank, by sizes for each of the methods of weighting.

It is evident that the method of weighting has little effect on order numbers in corresponding positions in the different sections of the table. In only one case is the order number changed by more than two places; and in all cases except one, the highest and the lowest order numbers occupy the same position. Three of these four methods are compared graphically in figure 22.

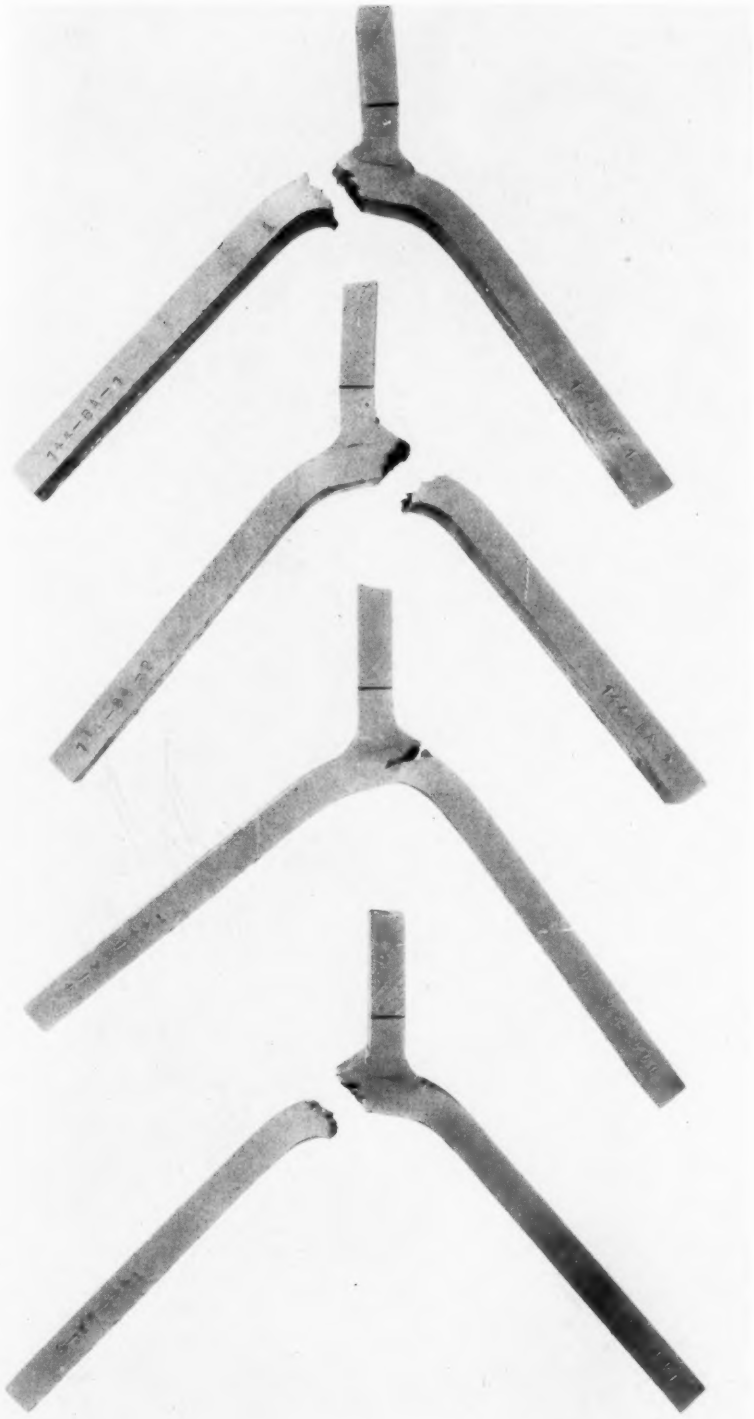

FIGURE 23.—*Steel 144, ½-in. plates, welded as rolled.*

Sharp fractures in the plate metals. Average angle at maximum load, 56°.

FIGURE 24.—*Steel 144, ½-in. plates, welded after normalizing treatment*

No failures. Average angle at maximum load, 68°.

TABLE 17.—*Comparison of weighted rank by sizes, for various methods of weighting*

[Steels welded and tested at all temperatures]

| Steel | ¼ in. | | ½ in. | | ¾ in. | | As rolled | | Normalized | | AR & N Comb. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AR | N | AR | N | AR | N | Total | Order | Total | Order | Total | Order |
| **TOTAL WEIGHTED RANK** (Weights: Angle 3, Deviation 3, Plate Failures 2, All Failures 1, Max. Load 1) | | | | | | | | | | | | |
| 139 | 33 | 66 | 18 | 50 | 60 | 58 | 111 | 5 | 174 | 5 | 285 | 5 |
| 144 | 14 | 53 | 41 | 64 | 28 | 60 | 83 | 6 | 177 | 4 | 260 | 6 |
| 146 | 71 | 76 | 68 | 74 | 65 | 67 | 204 | 1 | 217 | 1 | 421 | 1 |
| 147 | 47 | 64 | 56 | 69 | 43 | 56 | 146 | 2 | 189 | 2 | 335 | 2 |
| 149 | 39 | 33 | 53 | 57 | 50 | 54 | 142 | 3 | 144 | 6 | 286 | 4 |
| 150 | 30 | 58 | 57 | 64 | 33 | 56 | 120 | 4 | 178 | 3 | 298 | 3 |
| Total | 234 | 350 | 293 | 378 | 279 | 351 | 806 | | 1,079 | | 1,885 | |
| Order | 6 | 3 | 4 | 1 | 5 | 2 | | | | | | |
| **RANK FOR ANGLE, DEVIATION, AND PLATE FAILURES ONLY** (Equal Weights) | | | | | | | | | | | | |
| 139 | 10 | 21 | 5 | 16 | 18 | 18 | 33 | 5 | 55 | 4 | 88 | 4 |
| 144 | 1 | 16 | 11 | 19 | 6 | 19 | 18 | 6 | 54 | 5 | 72 | 6 |
| 146 | 23 | 25 | 22 | 24 | 19 | 20 | 64 | 1 | 69 | 1 | 133 | 1 |
| 147 | 14 | 21 | 18 | 23 | 11 | 16 | 43 | 2 | 60 | 2 | 103 | 2 |
| 149 | 11 | 9 | 16 | 17 | 14 | 16 | 41 | 3 | 42 | 6 | 83 | 5 |
| 150 | 8 | 19 | 19 | 21 | 10 | 18 | 37 | 4 | 58 | 3 | 95 | 3 |
| Total | 67 | 111 | 91 | 120 | 78 | 107 | 236 | | 338 | | 574 | |
| Order | 6 | 2 | 4 | 1 | 5 | 3 | | | | | | |
| **AVERAGE ANGLE AT MAXIMUM LOAD (Unweighted)** | | | | | | | | | | | | |
| 139 | 59x | 66 | 56x | 65x | 63x | 63 | 59.3 | 4 | 64.7 | 3 | 62.0 | 3 |
| 144 | 52 | 61 | 60 | 66 | 54 | 61 | 55.3 | 6 | 62.7 | 5 | 59.0 | 6 |
| 146 | 65 | 66 | 68 | 68 | 64 | 64 | 65.7 | 1 | 66.0 | 1 | 65.8 | 1 |
| 147 | 62 | 64 | 64 | 68 | 60 | 62 | 62.0 | 2 | 64.7 | 2 | 63.3 | 2 |
| 149 | 59x | 58x | 63 | 64 | 59 | 60 | 60.3 | 3 | 60.7 | 6 | 60.5 | 5 |
| 150 | 57 | 62 | 62 | 64 | 58 | 62 | 59.0 | 5 | 62.7 | 4 | 60.8 | 4 |
| Ave | 590 | 628 | 622 | 658 | 597 | 620 | 60.3 | | 63.6 | | 61.9 | |
| Order | 6 | 2 | 3 | 1 | 5 | 4 | | | | | | |
| **PERCENT PLATE FAILURES (Unweighted)** | | | | | | | | | | | | |
| 139 | 98 | 46 | 96 | 74 | 57 | 53 | 84 | 5 | 57 | 5 | 71 | 4 |
| 144 | 100 | 65 | 99 | 69 | 81 | 32 | 93 | 6 | 55 | 4 | 74 | 6 |
| 146 | 25 | 3 | 46 | 28 | 57 | 45 | 42 | 1 | 25 | 1 | 34 | 1 |
| 147 | 97 | 31 | 57 | 34 | 93 | 75 | 82 | 4 | 47 | 3 | 64 | 3 |
| 149 | 96x | 83x | 72 | 57 | 66 | 56 | 77 | 3 | 64 | 6 | 72 | 5 |
| 150 | 94 | 26 | 28 | 24 | 84 | 44 | 69 | 2 | 31 | 2 | 50 | 2 |
| Ave | 85 | 42 | 66 | 48 | 73 | 51 | 75 | | 47 | | 61 | |
| Order | 6 | 1 | 4 | 2 | 5 | 3 | | | | | | |

The relations between the weighted ranks and the tensile properties of the steels are shown in figure 25. At the top and bottom of the chart the steel numbers, in both conditions, are plotted against the weighted rank for each size.

There was no definite correlation between weighted rank and the yield point or the ultimate strength. The weighted ranks were apparently higher in steels with lower strengths, due largely to the abnormally high values of yield points and ultimate strengths for steel 144, which were imparted by a low finishing temperature in rolling. With the elimination of these values from consideration in the as-rolled plates, there was practically no correlation in this condition. In the normalized condition, there was no relationship whatsoever.

Also there was no definite correlation between the weighted rank and the elongation. For ¼-in. as-rolled plates, in general, the steels having the highest weighted rank had high values of elongation. However, this relationship did not exist in normalized ¼-in. plates, or in any of the ½- or ¾-in. plates.

The relations of angle at maximum load to the tensile properties are shown in figure 26. As explained previously, the angle at maximum load was assigned the greatest weight and dominates the weighted rank values. The curves in figure 26 follow very closely those of figure 25, and no good relationship was found between the angle at maximum load and the tensile properties for any of the plates.

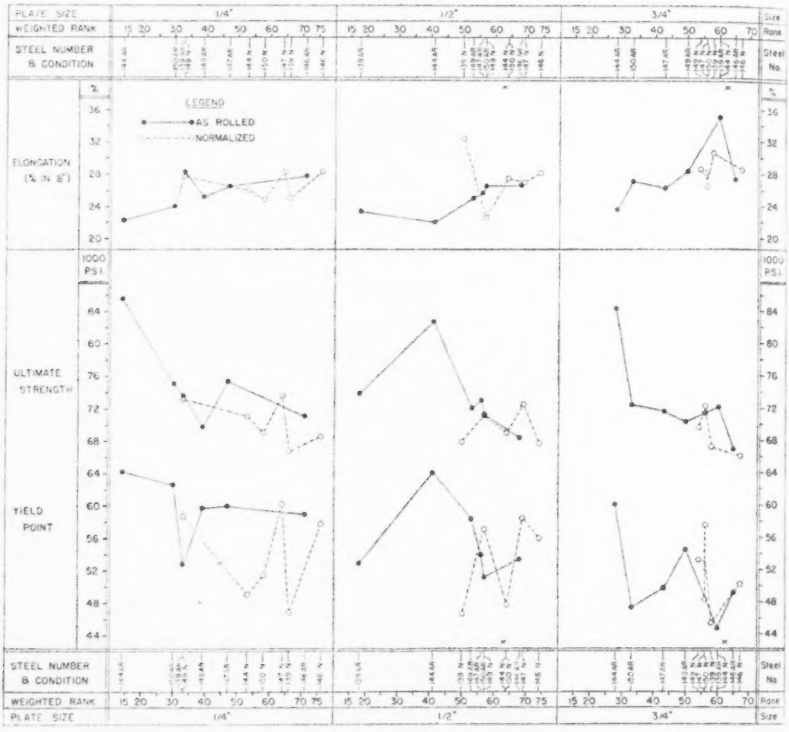


FIGURE 25.—*Relation of weighted rank to tensile properties.*

Because failures in the plates were considered undesirable, it was deemed advisable to determine whether any of the tensile properties influenced the location of the failures. The relation between the percentage of plate failures and the tensile properties is shown in figure 27. It should be noted that the scale is reversed, so that steels with the least percentage of failures (considered the most desirable) are placed at the right. It is evident that there is no definite correlation between the percentage of plate failures and any of the tensile properties.

There was an apparent correlation between weighted rank and Vickers numbers of the unwelded plates in the as-rolled ¼-in. thickness

(fig. 28). There was no correlation for the normalized ¼-in. plates nor for any of the other thicknesses. There is no correlation between the weighted rank and either the highest Vickers numbers or increase in Vickers numbers. The numbers for the unwelded plates lie within a rather narrow range (145 to 180), most of them between 150 and 170. After welding, none of the Vickers numbers were high—the greatest increase in as-rolled plates being 100 in steel 144 (½-in. thickness) and in the normalized plates about 115 in steel 147 (½-in. thickness).

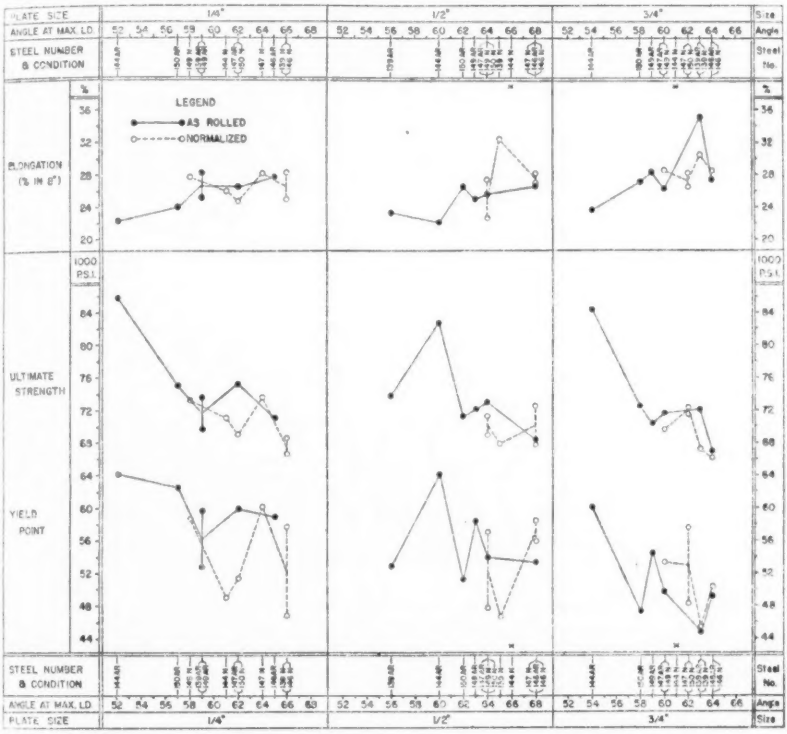


FIGURE 26.—*Relation of angle at maximum load to tensile properties.*

The relations between angles at maximum loads and Vickers numbers are shown in figure 29. It is evident that there was no good correlation in either rolled or normalized conditions.

The relations between the percentage of plate failures and Vickers numbers are shown in figure 30. There was no correlation in any thickness or condition.

Figures 31, 32, and 33 show, respectively, the relation of weighted rank, angle at maximum load, and percentage of plate failures to the chemical compositions of the plates. The percentage by weight of each of the 10 elements listed in the first column of each chart is shown for each steel and thickness. The chemical compositions of the as-rolled and normalized steels are the same, since they were taken from the same original plate, but the as-rolled and normalized steels

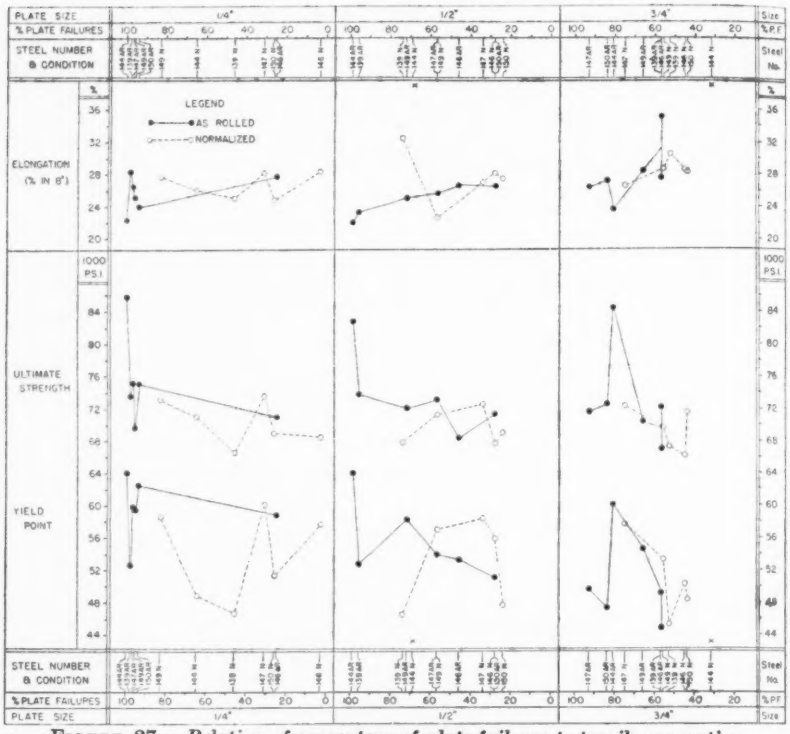


FIGURE 27.—*Relation of percentage of plate failures to tensile properties.*

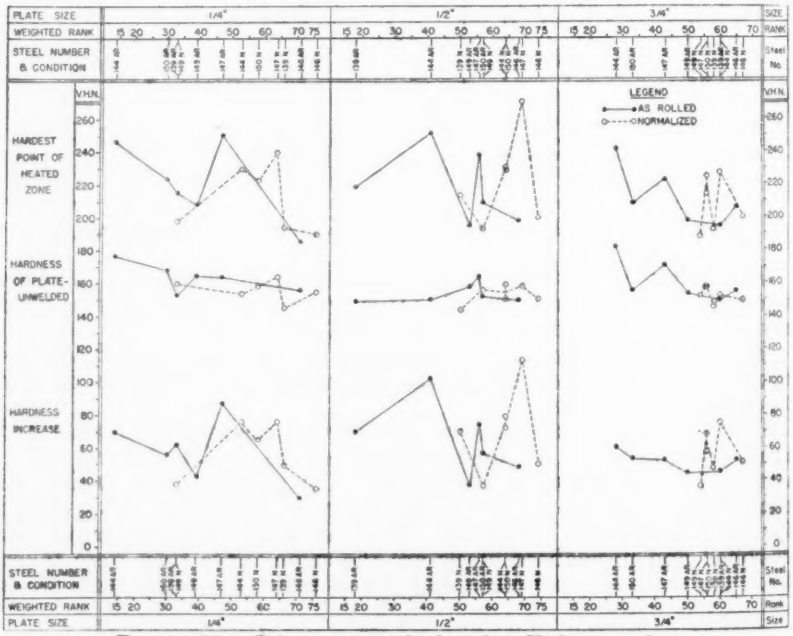


FIGURE 28.—*Relation of weighted rank to Vickers numbers.*

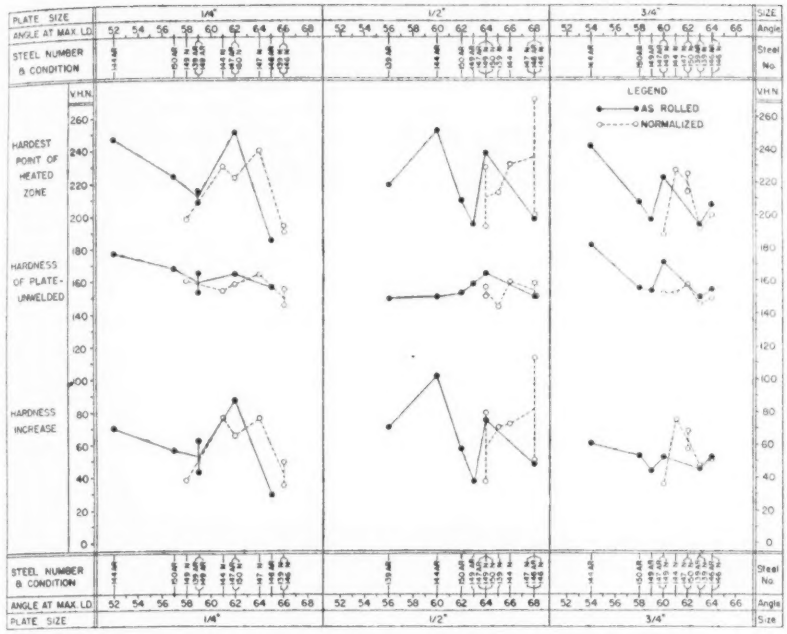


FIGURE 29.—*Relation of angle at maximum load to Vickers numbers.*

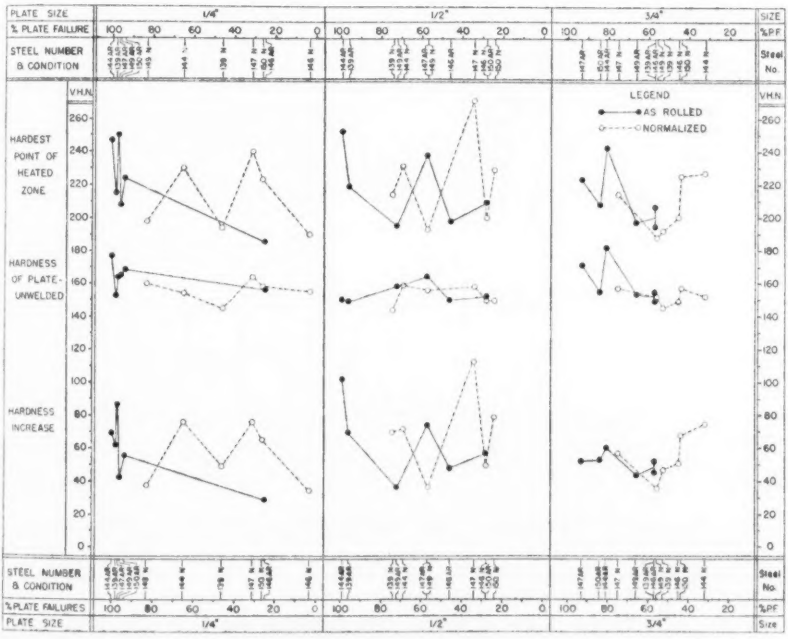


FIGURE 30.—*Relation of percentage of plate failures to Vickers numbers.*

are plotted separately to show the relation of chemical compositions to the ratings for both conditions of treatment. It will be noted also that the compositions for the different sizes of the various steels were

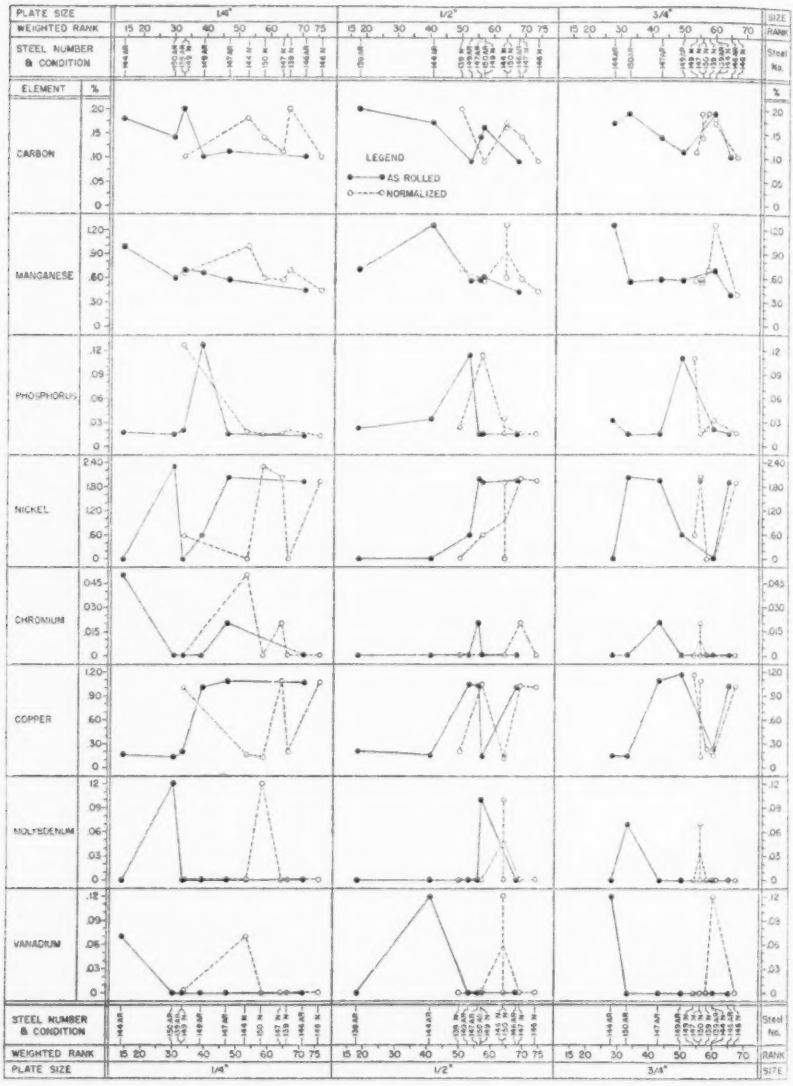


FIG. 31.—*Relation of weighted ranks to chemical compositions of plate metals.*

not always the same, because the plates of different sizes were probably furnished from different heats.

It is difficult to draw definite conclusions on the effect of each chemical element. In some steels certain elements were found only

in small or insignificant amounts; in others, the effect of one element was offset or masked by one or more other elements which might have had an appreciable influence on the weldability of a steel. The

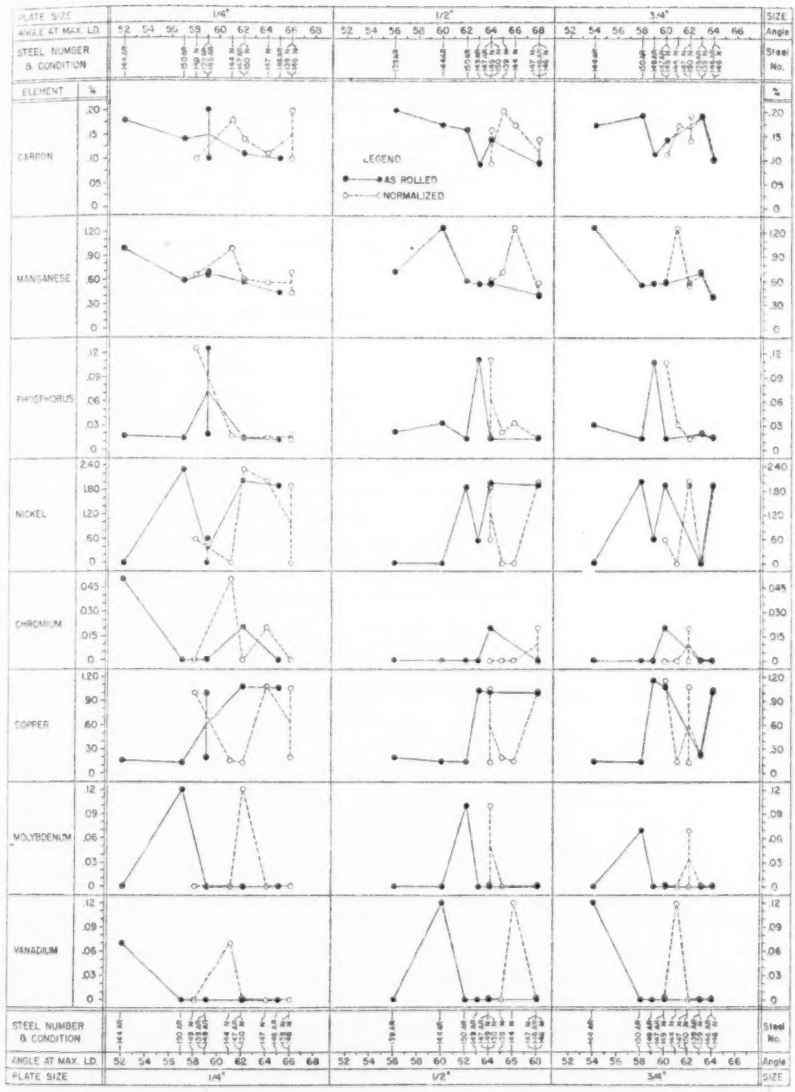


FIG. 32.—*Relation of angle at maximum loads to chemical compositions of plate metals.*

results for some steels in the normalized condition were widely different from those obtained on the same steel in the as-rolled condition, making it difficult to ascribe inferior bending properties or location of failure to a particular element. The effects of these elements are summarized below.

1. *Carbon.*—The range of carbon was 0.10 to 0.20 percent. In the as-rolled condition, the steels having less than 0.15 percent of carbon had greater angles of bend and higher weighted ranks than those having more carbon. In the normalized condition, the carbon

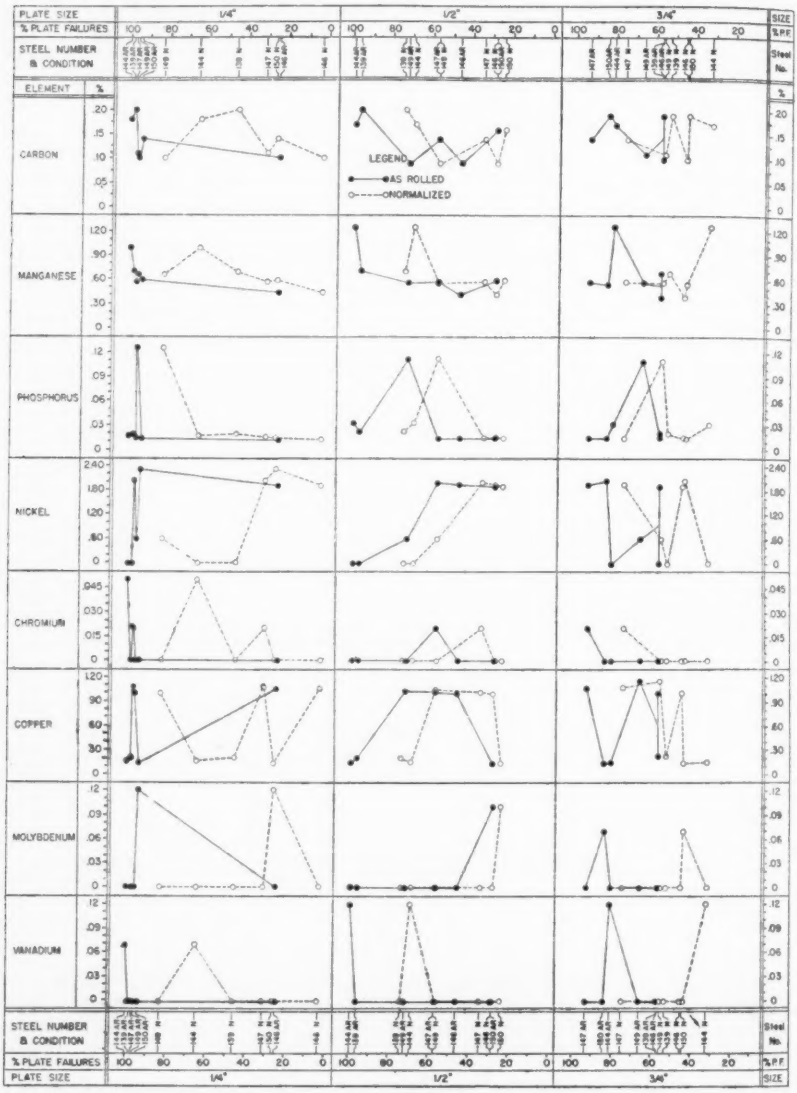


FIG. 33.—*Relation of percentage of plate failures to chemical compositions of plate metals.*

had no appreciable effect on the angle of bend or the weighted rank. Carbon had no effect on the number of plate failures.

2. *Manganese.*—The manganese did not exceed 0.70 percent except in steel 144, which in the as-rolled condition had the greatest number

of plate failures, the lowest angles of bend, and the lowest weighted ranks of any steel.

This steel was very "dirty," containing many inclusions of manganese sulfide. Usually dirty steels have poor welding quality because of discontinuities at the inclusions, which decrease the ductility, especially transversely, and prevent good cohesion between the weld metal and the plate metal. These effects are greater if the steel has been finish-rolled at low temperatures to increase the tensile properties.

It is evident from figures 31, 32, and 33 that as the amount of manganese is greater the angle of bend and the weighted rank are less and the number of plate failures is greater. This effect is less marked in the normalized condition.

3. *Phosphorus* was an alloying element in one steel, 149. Although the angles of bend and weighted rank were good, there were many plate failures.

4. *Sulfur* was present from 0.019 to 0.044 percent and in this range had no appreciable effect on the welding quality.

5. *Silicon* between 0.14 and 0.21 percent had no appreciable effect on the welding quality.

6. *Nickel* in alloying amounts was present in four of the six steels, ranging from 0.60 to 2.32 percent. Some steels with appreciable amounts of nickel had high weighted ranks and high angles of bend, others had low values. Nickel did not have an appreciable effect on the bending properties of the steels. Other elements in these steels had as much or more effect on these properties than nickel in the range of compositions investigated.

7. *Chromium* was present in such small amounts that no conclusions could be drawn as to its effect on the welding quality.

8. *Copper* in amounts of 1 percent or more was present in three steels, all of which contained nickel, and one of which, 149, contained about 0.12 percent of phosphorus. For steels 146 and 147 in the as-rolled condition the angles of bend and weighted ranks were good, but they were slightly low for steel 149. Steel 146 had the lowest percentage of plate failures of the as-rolled steels, while steels 147 and 149 had high percentages. In the normalized condition, steels 146 and 149 had about the same values of weighted rank and angles at maximum load as in the rolled condition, and steel 147 had considerably higher values. All steels had somewhat lower percentages of plate failures in the normalized condition than in the rolled condition. The high-copper steels containing nickel consistently had high values of weighted ranks and angles at maximum loads. Copper-nickel steels had good bending properties after welding. Steel 149, containing 0.12 percent of phosphorus and 0.60 percent of nickel, had bending properties somewhat inferior to steels 146 and 147, containing normal phosphorus, 1.00 percent of nickel, and 2.00 percent of copper.

9. *Molybdenum.*—Only one steel contained molybdenum. This steel also contained approximately 2 percent of nickel. In the as-rolled condition the weighted ranks and angles at maximum load were low and the percentages of plate failures high. In the normalized condition the bending properties were improved considerably and the steel was satisfactory as to welding quality.

10. *Vanadium* was found in only one steel, 144. In the as-rolled condition, there were many plate failures and the angles and weighted ranks were low. In the normalized condition, however, there were

fewer plate failures; the angle of bend and the weighted ranks were high. The effect of vanadium may have been masked by the high manganese content. It is believed from previous tests that vanadium is beneficial in medium manganese steels.

## VI. PARTIALLY COMPLETED TESTS

In addition to the six steels which were investigated completely under all of the proposed conditions of welding and testing, several other steels were investigated only in part. The complete program of bending 408 specimens for each steel required considerable time; therefore if bending tests at room temperature indicated that the welding quality of a steel was poor, no tests were made at low temperatures.

For some steels only sufficient material was furnished for the tests at room temperature and for others only the ¼- and ½-in. plates were submitted.

The reasons for not making all of the tests are as follows:

| *Steel* | *Reason for not making all of the tests* |
|---|---|
| 138 | Failure to comply with requirements for tensile properties, type II fractures. |
| 140 | Failure to comply with requirements for tensile properties, type III fractures. |
| 141 | Failure to comply with requirements for tensile properties, low bending angle, type III fractures. |
| 143 | Low angle of bend, type III fractures. |
| 145 | Laminated plates, low angle of bend, type III fractures. |
| 148 | Low angle of bend, type III fractures. |
| 157 | Laminated plates, low angle of bend, type III fractures. |
| 161 | Type III fractures. |
| 163 | No ¾-in. plates, low angle of bend, type II fractures. |
| 166 | No ¾-in. plates. Failure to comply with requirements for tensile properties. |
| 168 | No ¾-in. plates. |
| 201 | No ¾-in. plates. Low bending angle, type II fractures. |

The weighted ranks and order number of all specimens tested at room temperature are given in table 18.

TABLE 18.—*Total weighted rank*

[Specimens welded and tested at room temperature]

| Steel | Total weighted rank and order number | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | As-rolled | | | | Normalized | | | |
| | ¼ in. | ½ in. | ¾ in. | Order No. | ¼ in. | ½ in. | ¾ in. | Order No. |
| 138 | ------- | 61 | 81 | 6 | 87 | 82 | 84 | 2 |
| 139 | ------- | 58 | 87 | 5 | 59 | 56 | 82 | 9 |
| 140 | ------- | 18 | 60 | 11 | 61 | 57 | 68 | 10 |
| 141 | 63 | 5 | 53 | 10 | 80 | 54 | 86 | 7 |
| 143 | 2 | 20 | 39 | 15 | 63 | 59 | 75 | 9 |
| 144 | 51 | 28 | 20 | 14 | 96 | 90 | 58 | 3 |
| 145 | 4 | 65 | 44 | 12 | 62 | 55 | 38 | 11 |
| 146 | 73 | 94 | 82 | 3 | 58 | 79 | 76 | 8 |
| 147 | 43 | 78 | 68 | 8 | 64 | 88 | 80 | 5 |
| 148 | 4 | 10 | 10 | 17 | 20 | 20 | 10 | 13 |
| 149 | 43 | 78 | 80 | 7 | 88 | 90 | 80 | 1 |
| 150 | 41 | 61 | 10 | 13 | 89 | 62 | 77 | 6 |
| 157 | 5 | 7 | 9 | 18 | 29 | 54 | 72 | 11 |
| 161 | 92 | 58 | 76 | 4 | 87 | 78 | 79 | 3 |
| 163 | 5 | 24 | ------- | 16 | 40 | 48 | ------- | 12 |
| 166 | 83 | 90 | ------- | 2 | 76 | 80 | ------- | 4 |
| 168 | 83 | 93 | ------- | 1 | 76 | 80 | ------- | 4 |
| 201 | 37 | 54 | ------- | 9 | 48 | 75 | ------- | 10 |

It is believed that to be satisfactory for welding, a steel should have a weighted rank of 50 in each thickness, one-half of the possible maximum weighted rank.

Steels 138, 139, 146, 166, and 168 in the as-rolled condition were the only ones which complied with this requirement. The weighted ranks of steels 147 and 149 had slightly low values for the ¼-in. plate thicknesses. Steel 141 had a value of only 5 in the ½-in. thickness. All other steels had low values in two or more thicknesses except steels 140 and 201, in which data were available for two thicknesses only.

The order numbers indicate the relative welding qualities of the steels in a manner similar to that of table 16. Two steels, 168 and 166, had higher ranks than steel 146, but these were not submitted in three plate thicknesses. Steel 166 also had low tensile strength.

For the normalized condition the weighted ranks were considerably higher than for the as-rolled condition. All steels had values of 50 or more in this condition except 145 (¾-in.), 148 (¼-, ½-, and ¾-in.), 157 (¼-in.), 163 (¼- and ½-in.), and 201 (¼-in.).

Normalizing greatly increased the welding quality of steels 144, 150, and 157. For steel 157 the weighted ranks for the ¼-, ½-, and ¾-in. plates as-rolled were 5, 7, and 9, and after normalizing were 29, 54, and 72, respectively. The tensile strength of this steel was about 85,000 lb/in.$^2$ in the rolled condition and only about 64,000 lb/in.$^2$ in the normalized condition, indicating that a considerable increase in tensile strength had taken place as a result of rolling. This is reflected in the low weighted rank values in the rolled condition.

Steel 144, the Navy Department's standard for construction purposes, likewise had low weighted ranks in the as-rolled condition—51, 28, and 20 for the three thicknesses. The corresponding weighted ranks for normalized plates were 96, 90, and 58. The steel also had been cold-finished in rolling to obtain high tensile strengths.

It should be stated at this point that, although the manganese vanadium steel (144) does not show to particular advantage when compared with certain other steels in this method of determining welding quality, the use of this type of steel in naval construction should not, in the opinion of the authors, be discontinued on this basis alone. Experience has shown that manganese vanadium steel is reasonably satisfactory in actual use and that its quality has improved constantly during the period of about 7 years that it has been employed. It is not considered advisable to embark on the extensive use of another type of steel until it is possible to conduct further experimentation at full scale, such as the construction of several vessels, to prove the actual advantages of those steels which show to better advantage in the present test. Current conditions preclude such experimentation, but it is hoped that after the present emergency such work may be undertaken.

Of like interest is the inconsequential improvement of steel 148. This steel was extremely dirty (fig. 1), to which poor welding quality was ascribed. Welding quality was not improved to any appreciable extent by normalizing, the weighted rank of the normalized specimens being far below that desired for weldable steels. This steel had the second lowest order in the as-rolled condition and the lowest in the normalized condition.

From most of the tests, steels which had been rolled at low temperatures in order to procure increased tensile strength generally had poor bending properties in the T-bend test. Many of these steels had considerably improved bending properties when the plates were normalized before welding.

Most excessively dirty or laminated steels did not have good bending properties. Such steels cannot be improved materially by normalizing, since nonmetallic inclusions cannot be eliminated or reduced by heat treatment.

## VII. TESTS OF CAST AND WELDED FILLETS

A simple demonstration was made to show that the results of the T-bend test depended not on the size and shape of the specimen but on the effect of welding on the plate metal. Several cast-to-shape specimens were prepared from steels of different carbon contents; some were cast T-specimens with fillets; others were T-specimens without fillets, which later were welded in the same manner as the other T-specimens.

The specimens with and without fillets were poured adjacent to each other in the same mold and from the same molten metal, so that variables were a minimum. All specimens were normalized at 1,650° F before the fillets were welded. Specimens with cast fillets had bending properties superior to those of specimens with welded fillets. Examples of specimens of 0.10-percent-carbon steel are shown in figure 34. The specimen at the top with cast fillets had an angle of 66° at maximum load and bent to 120° without failure. The specimen at the bottom with welded fillets had an angle of 52° at maximum load and bent only to 63° before failure in the plate with a sharp report (type III fracture).

Similar tests made on specimens of 0.20-, 0.30-, 0.40-, and 0.50-percent-carbon steels gave similar results. Specimens with welded fillets, normalized after welding, had bending properties similar to those for specimens with cast fillets.

## VIII. TESTS OF SPECIMENS OF VARIOUS WIDTHS

The nominal width of specimens was 1¼-in. To determine whether variations in this width would cause appreciable differences in bending properties, specimens of widths ranging from ½- to 1½-in. were machined from the same welded joints in ½-in. plates and tested.

Maximum loads were less for narrow specimens and higher for wider specimens than for those of nominal width. This was due primarily to the mass of metal in the joint, as previously discussed.

In the range from about ¾- to 1½-in., the angles of bending were not affected to any appreciable extent, all values falling within the usual scatter of the nominal size specimens. Specimens ¾-in. or less in width bent with slightly larger angles than normal, caused probably by edge effect. Specimens wider than 1½-in. could not be tested because of the limitations of the jig.

The type of fracture was the same regardless of width. It was not possible to change the type of fracture of the nominal width specimen from sharp (type III) to gradual (type II) or from plate (types II and III) to bond or weld (type I), or vice versa, by either increasing or decreasing the width of the specimen.

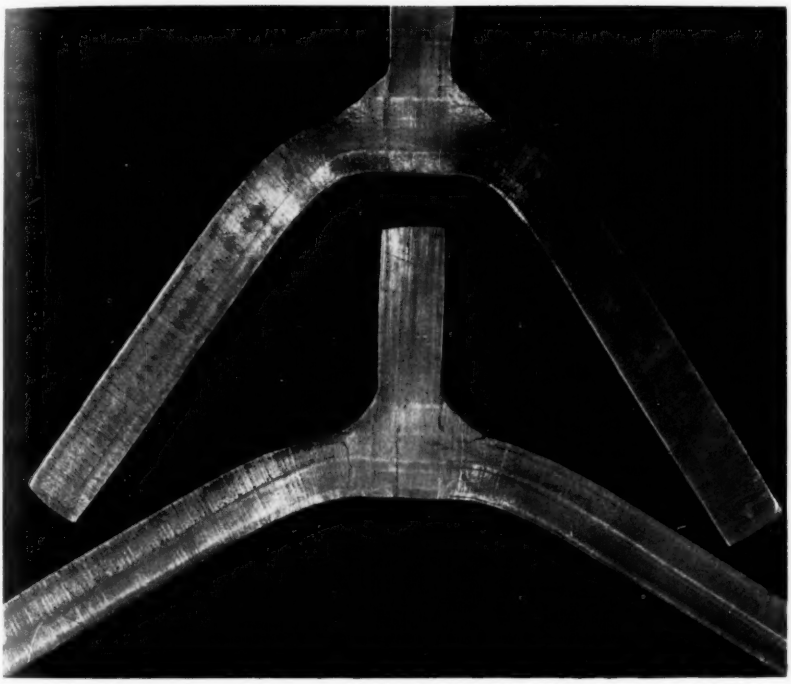

FIGURE 34.—*Cast and welded fillets tested in T-bend jig.*

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The results of these tests indicate that minor departures from nominal widths, such as might be caused in the machining of specimens, had no appreciable effect on either the angle of bend or the type of fracture.

## IX. SUMMARY

A method for testing the welding quality of steels has been described. Specimens of double fillet-welded T-sections were bent in a special bending jig.

Eighteen steels, generally in three thicknesses, ¼-, ½-, and ¾-in., and in two conditions, as-rolled and normalized, were tested. Some specimens were welded when the plates were at room temperature, others were made when the plates were at subnormal temperature as low as −20° F. Bend tests were made on these specimens at temperatures ranging from 70° to −20° F.

The angle of bend at maximum load and the type of fracture were the principal factors in determining welding quality.

A special method of analysis was used to evaluate the data.

No good correlation was found between any of the usual tensile properties or Vickers numbers of the steels and weldability; therefore they cannot be used for determining the welding quality.

Usually normalized plates had higher welding quality than the as-rolled plates of the same steels, due probably to relief of stresses set up during rolling and to a more homogeneous structure of the metal.

Most "dirty" steels had lower welding quality than clean steels.

Austenitic grain size and grain-coarsening temperatures apparently had little effect on welding quality.

Steels containing nickel and copper had the highest welding qualities of the steels tested, while those containing more than 0.70 percent of manganese had the lowest welding quality. Phosphorus greater than 0.10 percent also is believed to contribute to low welding quality in steels.

Plates welded at low temperatures had lower angles of bend and more plate metal failures than those welded at room temperature. The temperature of testing apparently had more effect on the angle of bend and plate metal failures than the temperature of the plates when welding was begun.

This bend test provides a reliable means for determining the welding quality of steels. A structural weld is tested without machining the surface, leaving the welds intact as deposited. The reproducibility of results of duplicate specimens is excellent. The angle of bending and the kind, extent, and location of the fractures are important criteria of the welding quality of steels and not a function of the shape of the specimen.

The views expressed in the foregoing paper are the personal opinions of the authors, and in no way express the opinions of the Navy Department and the National Bureau of Standards.

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U. S. Department of Commerce National Bureau of Standards

RESEARCH PAPER RP1445

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# EXPANSIVITY OF A VYCOR BRAND GLASS

By James B. Saunders

**ABSTRACT**

In a study of a new glass (96 percent silica, glass No. 790) used in heat-resisting glassware, its expansivity is compared with that of fused quartz. For this comparison a modification of Fizeau's method for determining very small differences in linear expansion was used and is presented. This method has the advantage of permitting the use of relatively long samples, the procurement of very sharp and well-defined interference bands, and the almost complete elimination of the effect of changes in the refractive index of air on the results.

The results indicate that the No. 790 glass has a coefficient of expansion approximately twice that of fused quartz at room temperature, an expansivity equal to fused quartz at approximately 300° C., and an expansivity less than one-half of that for fused quartz, in the neighborhood of 700° C.

A study of the physical properties of the new glass (96 percent silica, glass No. 790) used in heat-resisting glassware is of particular interest, since its manufacture demands a process [1] quite different from that used in making most glasses. On heating this glass from room temperature to 900° C., the expansivity is found to vary from approximately twice to less than one-half that of fused quartz. The proximity of these values to those of fused quartz and the exceptionally large percentage decrease in expansivity with increasing temperature are believed to be of general interest.

In the determination of expansivities of materials with such low expansion as fused quartz and glass No. 790, the usual methods do not permit of high precision. The usual interferometer method [2] is ordinarily as good as any, but the accuracy of its results depends upon an accurate knowledge of the changes in the refractive index of air with temperature. The change in the refractive index of air requires a relatively large correction when low-expansion materials are being measured.

In this work a modification of Fizeau's differential interferometer method [3] was used. That is, the three adjustable screws used by Fizeau to support the top plate were replaced by a fused-quartz tube. The length of this tube and that of the test specimen were chosen so that the resulting air correction was very small. Obviously this

[1] Glass Industry **20**, 269 (1939). See also U. S. Patents 2,106,744 and 2,150,694.
[2] G. E. Merritt, BS, J. Research **10**, 59 (1933) RP515. See also improvements by the author: J. Research NBS **23**, 179 (1939) RP1227.
[3] Ann. Phys, **128**, 564 (1866).

differential method also permits the use of specimens much longer than the usual interferometer method. It thus yields an accuracy in the difference between the expansivity of the sample and that of fused quartz which is believed to be much better than the accuracy of the accepted values for the expansivity of fused quartz. This particular modification of Fizeau's method may or may not be new.

Since the expansion of fused quartz is well known, a comparison of the expansion of No. 790 with that of fused quartz by the method described below will yield the value for No. 790 with an accuracy limited only by the accuracy with which that of fused quartz is known.

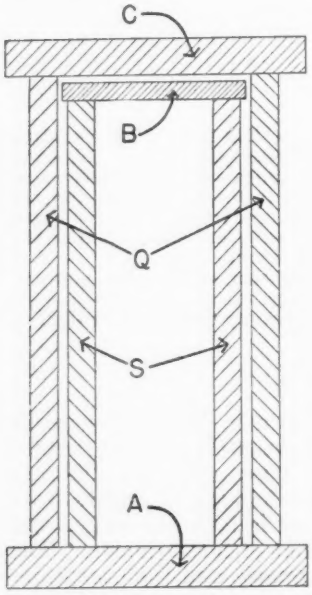


FIGURE 1.—*Schematic drawing of the differential interferometer.*

Figure 1 is a diagrammatic view of the interferometer arrangement used. The specimen of No. 790 is represented by $S$ and is in the form of a tube. A similar tube of fused quartz, having an inside diameter larger than the outside diameter of the No. 790 specimen, is represented by $Q$. The plates $A$, $B$, and $C$ are made of fused quartz with plane surfaces. Plate $B$ is fine ground on the lower face and polished on its upper surface, the two surfaces being parallel. Plate $C$ is polished on both faces, which, however, are not quite parallel. The two ends of each tube are ground so that when they stand vertically on a horizontal surface, only three points, equally spaced, are in touches with the base plate and so that a plate resting on the tube (as $B$ on $S$, fig. 1) contacts the tube at only three equally spaced points. The lengths of the tubes are adjusted so as to have a very thin air space between plates $B$ and $C$. Temperature was determined by means of a thermocouple, the junction of which was located just below the center of the lower surface of plate $A$. The No. 790 specimen used was approximately 48 mm in length; the fused quartz tubing, 52 mm long; and the thickness of plate $B$, 3 mm. Much longer samples may be tested by this method, and the air space between plates $B$ and $C$ may be made less than 0.1 mm if the differential expansion permits.

When the various parts of the interferometer are properly adjusted, the two polished surfaces bounding the air space between plates $B$ and $C$ are nearly enough parallel to produce good broad interference bands when monochromatic light is used. The shortness of the light path between these two reflecting surfaces permits the procurement of sharp, brilliant bands such as are not obtainable in the usual method [4] because the latter requires longer paths. The elimination of air-film errors was accomplished by overweighting one of the supports of each plate, $B$ and $C$, and applying the correction factor explained in a previous paper.[5]

[4] See footnote 2.
[5] J. B. Saunders, J. Research NBS 23, 186 (1939) RP1227.

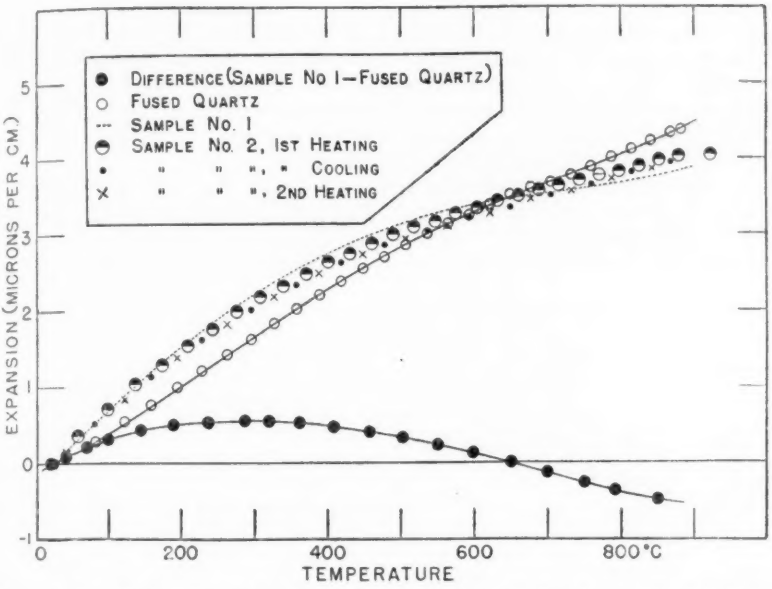


FIGURE 2.—*Expansion and differential expansion of fused quartz and Vycor (96 percent silica, glass No. 790).*

The difference between the expansion of a specimen of No. 790 (represented as sample No. 1) and fused quartz was obtained by means of the above method, and the results are shown in figure 2 by the closed circles. An independent determination, using the usual method given in footnote 2, was made on a sample of fused quartz which was taken from the same tube used in the above test. The results of this test are indicated by the open circles in figure 2. By applying the "Method of Averages," an empirical formula was found which fitted the data for the fused quartz within the errors of observation. The resultant formula is represented by the curve which passes through the open circles. A second formula was computed in the same manner to fit the differential-expansion data. By adding the corresponding ordinates representing the expansions obtained from these two formulas, a third formula representing the expansion of sample No. 1 was obtained. This third formula is represented in figure 2 by the dotted curve.

To check these results of the differential method, a second sample of Vycor No. 790 (sample No. 2) was used. The usual interferometer method was applied to obtain the expansion of this sample at various temperatures, and the results are indicated in figure 2 by the half-closed circles. The discrepancy between the two samples of Vycor is not surprising, since the correction arising from the changes in the refractive index of air is large compared to the fringe shift when the usual interferometry method is applied in air. Also, the two samples could easily yield different values, since sample No. 1 was taken from a relatively thin-walled tube and sample No. 2 from a flask having much thicker walls.

The points indicated by the small closed circles in figure 2 represent expansion data taken on sample No. 2 while cooling after the first heating to 920° C. The crosses represent data taken during a second heating. These two sets of data fall on a common curve, as is to be expected. The lack of coincidence of these data with those of the first heating probably arises from a slight contraction of the specimen, due to annealing, at the higher temperatures.

A comparison of the expansivity of Vycor No. 790 with that of fused quartz is shown in figure 3. The curves were obtained from the three expansion formulas mentioned above, by differentiation with respect to temperature, which gives the slopes of the expansion curves.

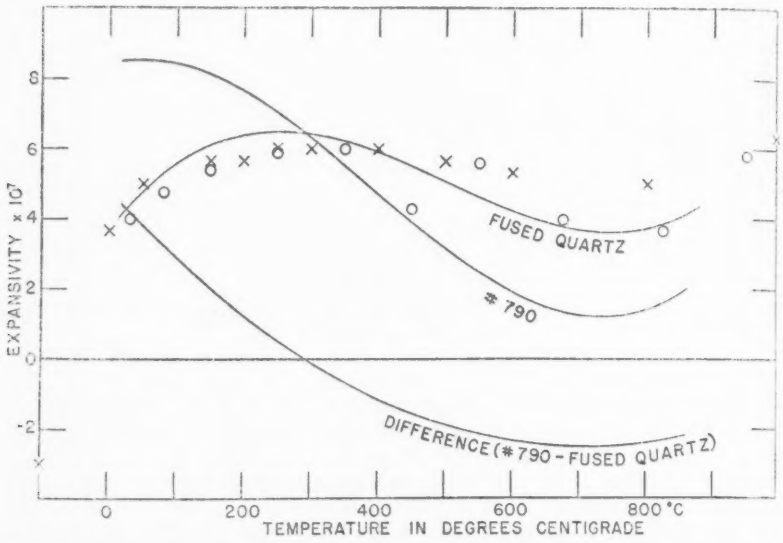


FIGURE 3.—*Expansivity of fused quartz and Vycor (96 percent of silica, glass No. 790).*

Crosses represent values selected by Sosman and circles represent values derived from Souder and Hidnert's data.

At room temperature the No. 790 glass has an expansivity approximately twice that of fused quartz, whereas at 300° C the two are nearly equal. At 700° C the expansivity of the sample of No. 790 is less than one-half that of fused quartz. Above 900° C the specimen either begins to deform under its own weight plus that of plate *B* or it undergoes density changes which are independent of temperature variations. It may be mentioned that most glasses have expansivities which increase with increasing temperature, whereas the above samples of No. 790 have a decreasing expansivity from room temperature up to 700° C and an increasing expansivity from there on to 900° C.

In order to eliminate errors arising from temperature gradients, each measurement was taken after temperature equilibrium had been well established. With the differential interferometer, the position of the two tubes (No. 790 and fused quartz) with respect to each

other insured that the average temperature of each, from end to end, was practically the same. However, any error in the temperature measurement which is of the same magnitude at all temperatures introduces no error in the expansivity values. The air correction for refractive-index changes in the air is almost nil for the differential data, but large for the absolute determinations. The average error in the difference between the expansivity of fused quartz and No. 790 is believed to be less than 2 percent. Although this accuracy is not attained in the direct measurements on fused quartz, it is believed that the values reported here are as good as any of those reported by other observers.

A comparison of expansivity values found for the fused quartz used in this test with those reported by other observers would seem to be of interest. For this purpose a series of points (indicated by crosses in fig. 3) are given and represent values computed from volumetric values which were selected by Sosman.[6] The results of work published by Souder and Hidnert [7] of the National Bureau of Standards is represented by the circles shown in figure 3. These latter points represent the average expansivity over temperature ranges, of which the abscissas are the average temperatures of these ranges.

WASHINGTON, August 19, 1941.

[6] R. B. Sosman, The Properties of Silica, chapter XX, table XX. 2, p. 362 (Chemical Catalog Co., Inc., New York, N. Y., 1927.)
[7] Sci. Pap. BS **21**, 1 (1926) S524.

U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

RESEARCH PAPER RP1446

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# SOIL-CORROSION STUDIES, 1939. COATINGS FOR THE PROTECTION OF METALS UNDERGROUND

By Kirk H. Logan

ABSTRACT

In this paper is reported the condition of specimens of metallic and nonmetallic coatings after exposure to soils for periods ranging from 2 to 16 years. Conclusions previously drawn relative to the protective value of zinc and lead coatings are generally confirmed by the latest inspections. A specially applied zinc coating prevented serious pitting in 16 soils over a 16-year period, but a commercial coating of the same weight, exposed to more corrosive soils, did not prevent pitting entirely during the initial 2-year period. Lead corrodes sufficiently in many soils to render lead coatings unsatisfactory. Tin applied as a protective coating was of little benefit in reducing the corrosion of copper in soils. A 7-year-old vitreous enamel, two 7-year old hard-rubber coatings, and a 2-year-old baked synthetic resin coating have shown little or no evidence of failure.

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## I. INTRODUCTION

The primary purposes of the field tests of pipe coatings being conducted by the National Bureau of Standards are (1) to furnish information on the protective value of various metallic and nonmetallic coatings to pipe-line operators and others concerned with the storage, transportation, and distribution of fluids underground, and (2) to assist in the development of improved coatings by studying their performance under a variety of soil conditions.

The selection of coatings for test has been largely in the hands of coating manufacturers, no attempt having been made to cover the field systematically. As the performance of coatings of a given type may vary, depending on details of manufacture, the results of the tests, particularly with respect to nonmetallic coatings, do not always justify generalizations regarding the different coatings as types. Nevertheless, the data obtained will be of value to those interested in the particular coatings tested and to those whose knowledge of coating materials enables them to make deductions concerning the possible results of modifications.

In considering the data to be presented, it should be remembered that service conditions are probably more severe than thoise under which the tests were made. Aside from the possibility of mproper application and injury to the coating during transportation and installation, the weight of pipe lines and their movement due to changes in temperature, and the stresses set up by shrinking and swelling of the soil with changes on moisture, etc., impose greater strains on coatings in service than on those applied to isolated sections of small pipe. Also, there is much less chance of a failure or defect occurring on a test specimen with an area of 0.67 square foot than, for example, on a pipe 20 feet in length and 8 inches in diameter, an area of 40 square feet. Although a small number of specimens of coated pipe or sheet may not constitute a representative sample, the performance of the specimens under a variety of environments affords some idea of the general usefulness of the coating in comparison with other coatings tested under the same conditions.

## II. METHODS OF TESTING

### 1. METALLIC COATINGS

Specimens of metallic coatings applied to both sheet and pipe were exposed to soil corrosion at 47 test sites in 1923 and 1924. Other series of tests of coatings applied to pipe were installed in 1932 and 1937 at an additional group of 15 sites. The soil conditions at six sites were similar in all of the tests. Ten specimens of each coating were buried at each site, two specimens being removed at each inspection. Beginning in 1932 the specimens were protected from shock and abrasion in transit by means of standard caps screwed on the threaded ends of the coated pipe. The threaded pipe was 1½-inches in diameter and of such length that one linear foot of coating was exposed between the capped ends.

The depth of the deepest pits and the loss of weight of the pipes, together with observations of the surface condition, were taken as measures of the effectiveness of the coatings. In the present report, corrosion losses are reported as the total loss in weight over the period rather than as a rate of loss. In previous reports, the losses were reported as rates in order to make the data for specimens differing slightly in age more nearly comparable. However, past experience has shown that no advantage is gained by using rates of loss of weight as criteria for comparing the corrosion on different coatings or metals. Even for a uniform material, corrosion is not usually proportional to the time of exposure, the nature of the corrosion-time relation depending in part on the corroding medium. Pit depths are somewhat

more indicative of the condition of a metal-coated specimen than is loss of weight, since the coating must be punctured before measurable pits can develop.

### 2. NONMETALLIC COATINGS

The methods of testing nonmetallic coatings have been altered somewhat since the first tests of coatings began. The coatings on which tests were started in 1924 were applied to steel pipe, 18 inches in length and 1½ inches in internal diameter, from which the mill scale had been removed by pickling. Five specimens of each coating were buried at each test site. One specimen was removed at intervals of 2 or more years and returned to the laboratory for examination. Ten specimens of the coatings buried in 1932 and later were exposed at each test site, and two specimens were removed every 2 years or at longer intervals. These coatings were applied by the manufacturer to pipe 1½ inches in internal diameter, 1 linear foot of coating being exposed for test. They were protected in handling by means of caps, as described in the previous section on metallic coatings. The specimens were inspected according to a definite system. The coating was then removed from one-half of the pipe and the depths of the deepest five pits were measured. Although the electrical resistance, or conductance, of coatings which might be classed as insulating materials has been used as a measure of the condition of the coating, this test was not employed in the present study. Conductance is not a satisfactory criterion for the condition of coatings that are not uniform in thickness nor for those which contain inhibiting chemicals or metallic or other conducting shields.

## III. METALLIC COATINGS

### 1. ZINC

#### (a) SPECIMENS EXPOSED 16 YEARS

Specimens of galvanized sheet and pipe were buried originally for the purpose of determining the importance of factors such as the thickness of the coating, the kind of base metal, and the exposure conditions. A detailed report [1] on the behavior of these and other coatings was prepared after the specimens had been exposed 10 years. The location of the test sites and data on the properties of the soils are given in this report. As specimens in many of the soils showed little or no corrosion after 10 years, it was decided to allow the specimens in the less corrosive soils to remain for a longer period. The condition of these specimens after 16 years is shown in table 1.

Since there were fewer specimens and the corrosiveness of the soils was relatively slight, the differences in behavior indicated by the data are not as striking as those presented in the earlier report. However, the conclusions reached in that report with regard to the importance of coating thickness and the negligible effect of the kind of base metal are borne out by the present data. For example, the protection afforded by the coating of 2.82 ounces per square foot on open-hearth iron pipe was such that measurable pits developed on the specimens in only a few of the soils over a period of 16 years. Some zinc remained on many of the specimens at the end of the test.

[1] Kirk H. Logan and Scott P. Ewing, J. Research NBS **18**, 361 (1936) RP982.

TABLE 1.—*Loss*[1] *of weight and depth of maximum penetration*[1] *of galvanized materials exposed for 16 years*

*a*=uniform corrosion.
*b*=hole due to union of pits from both sides of sheet.
*c*=no coating left on specimen.
*U*=no pitting.
*M*=metal attack—pits less than 1 mil in depth.
*P*=pits not greater than 6 mils in depth.
+=specimen punctured.

| Soil | | Sheet[1] | | | | | | Pipe | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Type | [3] 0.99 oz/sq ft on open-hearth iron | | 0.81 oz/sq ft on Bessemer steel | | 1.07 oz/sq ft on copper-bearing steel | | 2.82 oz/sq ft on open-hearth iron [4] | | Uncoated Bessemer steel [5] | |
| | | Loss of weight | Penetration | Loss of weight | Penetration | Loss of weight | Penetration | Loss of weight | Penetration | Loss of weight | Penetration |
| | | *oz/ft*[2] | *Mils* | *oz/ft*[2] | *Mils* | *oz/ft*[2] | *Mils* | *oz/ft*[2] | *Mils* | *oz/ft*[2] | *Mils* |
| 2 | Bell clay | 1.52 | 21 | 1.27 | 14 | 1.47 | 16 | 1.67 | 14(*c*) | 7.12 | 58 |
| 5 | Dublin clay adobe | 4.31 | 26(*a*, *c*) | 4.26 | 28(*a*, *c*) | 3.49 | 20(*a*, *c*) | 3.23 | *P* | 8.58 | 68 |
| 6 | Everett gravelly sandy loam | 0.96 | *U* | 0.91 | *P* | 0.70 | *P* | 0.37 | *P* | 1.88 | 23 |
| 7 | Maddox silt loam | 5.19 | 54(*b*, *c*) | | | | | 7.39 | 11(*c*) | 5.06 | 57 |
| 9 | Genesee silt loam | 1.90 | 36 | 1.81 | 37 | 1.77 | 30 | 1.64 | *M* | 5.10 | 74 |
| 12 | Hanford fine sandy loam | 0.89 | *M* | 1.00 | *P* | 0.75 | *P* | [6] 1.09 | [6] 11 | 5.32 | 99 |
| 17 | Keyport loam | 7.44 | 36(*c*) | 6.17 | 29(*c*) | 6.16 | 30(*c*) | 3.93 | 18(*c*) | 9.51 | 52 |
| 24 | Merrimac gravelly sandy loam | 0.43 | *P* | 0.27 | *P* | 1.14 | *P* | [6] 0.32 | [6] *P* | 1.56 | 42 |
| 25 | Miami clay loam | | | | | | | 1.76 | *P* | 2.73 | 70 |
| 26 | Miami silt loam | 1.37 | 22 | 1.15 | 16 | 1.36 | 17 | 1.25 | *P* | 4.77 | 62 |
| 27 | Miller clay | 2.45 | 12 | 2.41 | 10 | 1.88 | 12 | 2.07 | *P* | 8.86 | 93 |
| 31 | Norfolk sand | 0.89 | *M* | 0.46 | *P* | 0.72 | *P* | 0.46 | *P* | 4.08 | 68 |
| 36 | Ruston sandy loam | 1.19 | *P* | .90 | 12 | 1.10 | *P* | .76 | *P* | 2.58 | 54 |
| 38 | Sassafras gravelly sandy loam | 0.56 | *M* | .49 | *P* | 0.54 | *P* | .42 | *P* | 2.81 | 37 |
| 41 | Summit silt loam | 1.54 | 58 | 1.41 | 62+ | 1.66 | 28 | | | 7.03 | 112 |
| 47 | Unidentified silt loam | | | | | | | 1.90 | *M* | 5.37 | 64 |

[1] Values for single specimens unless otherwise indicated.
[3] Area approximately 110 inches of exposed coating.
[3] Weight of coating on one side. This is half the nominal weight of the coating on sheets.
[4] Two-inch pipe, 17 inches long.
[5] 3-inch pipe, 10 inches long. This pipe was buried in 1922.
[6] Average of 2 specimens.

(b) SPECIMENS EXPOSED 2 YEARS

The marked protective value of heavy zinc coatings, which was indicated by the inspection of the 10-year-old specimens, led to the burial in 1937 of steel specimens with a coating having a weight of 3.08 ounces per square foot at the 15 sites previously mentioned. The condition of these specimens after 2 years is shown in table 2. Unless otherwise stated, the values shown in this and in succeeding tables are averages of measurements made on two specimens.

TABLE 2.—*Loss of weight and depth of maximum penetration of galvanized and black iron pipe exposed 2 years*

| Soil | | Galvanized pipe 3.08 oz/ft² | | Black iron pipe | | Condition of coating [1] |
|---|---|---|---|---|---|---|
| No. | Type | Loss of weight | Penetration | Loss of weight | Penetration | |
| | | *oz/ft²* [2] | *Mils* | *oz/ft²* | *Mils* | |
| 51 | Acadia clay | 3.32 | 6 | 7.48 | 52 | 2 |
| 53 | Cecil clay loam | 0.26 | 9 | 1.77 | 42 | 1 |
| 55 | Hagerstown loam | .34 | 5 | 1.80 | 33 | 1 |
| 56 | Lake Charles clay | 3.68 | 5 | 13.78 | 77 | 3 |
| 58 | Muck | 4.29 | 13 | 5.08 | 29 | 3 |
| 59b | Houghton muck | 1.20 | 8 | 1.47 | 12 | 2 |
| 60 | Rifle peat | 4.27 | 10 | 4.03 | 15 | 3 |
| 61 | Sharkey clay | 0.64 | 6 | 2.24 | 40 | 1 |
| 62 | Susquehanna clay | 1.03 | 12 | 3.21 | 40 | 1 |
| 63 | Tidal marsh | 1.16 | [2] *P* | 2.74 | 24 | 1 |
| 64 | Docas clay | 5.16 | 8 | 8.72 | 80 | 3 |
| 65 | Chino silt loam | 1.09 | *P* | 4.30 | 50 | 2 |
| 66 | Mohave sandy loam | 1.59 | 6 | 9.23 | [3] 145+ | 1 |
| 67 | Cinders | 6.74 | 62 | 40.47 | 145+ | 3 |
| 70 | Merced silt loam | 2.08 | 8 | 4.93 | 50 | 1 |

[1] 1=coating on more than 50 percent of surface.
2=coating on less than 50 percent of surface.
3=little or no coating remaining.
[2] *P*=no pits greater than 6 mils.
[3] +=one or both specimens punctured.

As will be seen in table 2, pits developed in the specimens of galvanized pipe at nearly every test site in 2 years. This result is inconsistent with the data of previously described tests, in which a coating of 2.82 ounces per square foot prevented pitting of the base metal in all but one of 47 soils over a 10-year period. Although certain of the soils in the second series of tests proved to be more corrosive than any in the original series, it is also true that six soil conditions were duplicated in the two series of tests, as previously stated.

This difference in behavior of specimens having coatings of nominally the same thickness is possibly to be ascribed to greater uniformity of the coating in the earlier tests for which the specimens were recoated individually, that is, a second coat was applied after the pipe had been cut into the desired lengths. This procedure might favor a relatively greater degree of uniformity of coating than is obtained by the usual hot-dip process. The impracticability of securing a perfectly uniform coating by the hot-dip process as used commercially has been previously noted.[2] [3]

Pits developing in steel protected by a thick, uniform coating would not be expected to spread and deepen at an appreciable rate. The high cathodic current density on the exposed areas of steel would

[2] H. S. Rawdon, Protective Metallic Coatings (The Chemical Catalog Co., New York, N. Y., 1928).
[3] E. C. Groesbeck and W. A. Tucker, BS J. Research **1**, 255 (1928) RP10.

reduce the galvanic current, and consequently the rate of removal of zinc in the vicinity of the exposed area would be very low. However, if the coating were not uniform in thickness, pits developing in areas where the zinc coating was thin would be expected to spread and deepen. With the removal of the thin layer of zinc surrounding the pit, the exposed cathodic area would become more and more difficult to protect cathodically, and as a consequence the galvanic current and rate of removal of zinc would be proportionately greater. In fact, the corrosion of zinc might even be accelerated because of the large cathodic area provided by extensive removal of zinc.

While the difference in behavior of the two groups of specimens having nominally thick coatings cannot definitely be attributed to differences in uniformity, this factor must be given due consideration before drawing final conclusions relative to the protective value of zinc coatings in soils.

## 2. LEAD

### (a) SPECIMENS EXPOSED 16 YEARS

All the specimens of lead-coated pipe which were buried in 47 soils in 1923 and 1924 were removed from the more corrosive soils in 1934, but one set of specimens was allowed to remain in the less corrosive soils until 1939. The condition of these latter specimens is shown in table 3. The average thickness of the lead coating was 1.05 mils. The maximum and minimum thicknesses obtained from 12 measurements were 2.50 and 0.30 mils, respectively.

The data of table 3 confirm the conclusions reached in the previous report (see footnote 1), namely, that lead coatings of the thickness applied do not afford adequate protection. As was observed in the earlier inspection, the coated specimens in many of the soils developed deeper pits than did the specimens of unprotected steel.

TABLE 3.—*Loss of weight and depth of maximum penetration of 1½-inch lead-coated pipe and Bessemer steel pipe exposed 16 years* [1]

| Soil | | Lead-coated | | Bessemer steel | | Condition of coating [5] |
|---|---|---|---|---|---|---|
| No. | Type | Loss of weight | Penetration | Loss of weight | Penetration | |
| | | *oz/ft²* | *Mils* | *oz/ft²* | *Mils* | |
| 5 | Dublin clay adobe | 8.90 | 104 | [3] 7.12 | 50 | 3 |
| 6 | Everett gravelly sandy loam | .36 | 14 | 2.03 | 18 | 0 |
| 7 | Maddox silt loam | 4.42 | 145+ | 5.82 | 50 | 3 |
| 9 | Genesee silt loam | [3] 1.64 | [3] 60 | 5.80 | 64 | 2 |
| 12 | Hanford fine sandy loam | [4] 1.32 | [4] 28 | 6.04 | 72 | 2 |
| 17 | Keyport loam | 7.02 | 49 | 9.54 | 41 | 3 |
| 24 | Merrimac gravelly sandy loam | .77 | 28 | 1.79 | 16 | 2 |
| 26 | Miami silt loam | 1.49 | 48 | 4.28 | 42 | 2 |
| 27 | Miller clay | 4.13 | 47 | 10.14 | 69 | 3 |
| 31 | Norfolk sand | .49 | 28 | 3.72 | 43 | 1 |
| 35 | Ramona loam | [3] .14 | [3] 10 | 1.51 | 8 | 0 |
| 36 | Ruston sandy loam | 1.27 | 24 | 4.13 | 55 | 3 |
| 38 | Sassafras gravelly sandy loam | 2.17 | 34 | 2.30 | 28 | 3 |
| 41 | Summit silt loam | 1.27 | 80 | 6.87 | 92 | 2 |

[1] Lead-coated pipe buried in 1923–24.
Bessemer steel pipe buried in 1922.
[2] Data on one specimen only.
[3] Average of 3 specimens.
[4] Average of 4 specimens.
[5] 0=coating over entire specimen.
1=coating on more than 50 percent of surface.
2=coating on less than 50 percent of surface.
3=little or no coating left.

### (b) SPECIMENS EXPOSED 7 YEARS

Improvements in the process of coating pipe with lead have been made since the first sets of specimens were buried in 1925. Accordingly, specimens of lead-coated pipe 14 inches long and 1½ inches in diameter and coated by the newer process were buried at 15 test sites in 1932. The average thickness of the coating was 1.44 mils, and the maximum and minimum thicknesses of a group of 12 measurements were 2.97 and 0.50 mils, respectively. The corrosion data are shown in table 4. In very few soils could the protection provided by the lead coating be considered adequate.

Since lead, unlike zinc, is cathodic to iron and steel, protection of the underlying metal is accomplished chiefly by isolating the base metal from the environment. The life of the coating would then be expected to be determined largely by the corrodibility of lead under the conditions of exposure. Unless the rate of average penetration of lead is small relative to the thickness of the coating, the life of the coating would obviously be short. Furthermore, if the corrosion of lead in soils takes the form of localized attack, or pitting, the potential difference between lead and the exposed steel would cause accelerated attack except under those conditions in which the steel might be polarized anodically. It is, therefore, of interest to consider the average and maximum penetrations of lead in the various soils. In table 5 are shown values for the average and maximum penetrations of specimens of various kinds of lead which had been exposed to the same soils for 2 years.

TABLE 4.—*Loss of weight and depth of maximum penetration of lead-coated and steel pipe exposed 7 years*

| Soil | | Lead-coated | | Low-carbon tube | | Condition of coating [1] |
|---|---|---|---|---|---|---|
| No. | Type | Loss of weight | Penetration | Loss of weight | Penetration | |
| | | *oz/ft²* [2] | *Mils* | *oz/ft²* | *Mils* | |
| 51 | Acadia clay | 9.23 | 104 | 11.50 | [2] 135+ | 3 |
| 53 | Cecil clay loam | 1.65 | 44 | 4.18 | 54 | 2 |
| 55 | Hagerstown loam | 1.10 | 44 | 3.21 | 57 | 1 |
| 56 | Lake Charles clay | 10.18 | [2] 140+ | 20.97 | [2] 125+ | 3 |
| 58 | Muck | 11.76 | 90 | 14.08 | 110 | 3 |
| 59a | Carlisle muck | .35 | 7 | 3.00 | 30 | 0 |
| 60 | Rifle peat | 2.44 | 60 | 7.63 | 17 | 1 |
| 61 | Sharkey clay | 3.32 | 70 | 5.65 | 63 | 2 |
| 62 | Susquehanna clay | 2.11 | 47 | 5.32 | 71 | 2 |
| 63 | Tidal marsh | .46 | [3] *P* | 7.07 | 70 | 1 |
| 64 | Docas clay | 1.63 | 56 | 35.58 | [2] 154+ | 2 |
| 65 | Alkali soil | 3.80 | 53 | 13.73 | 83 | 3 |
| 66 | Mohave sandy loam | 4.41 | 61 | 14.34 | [2] 154+ | 2 |
| 67 | Cinder | [4] *D* | [2] 145+ | 23.54 | [2] 127+ | 3 |

[1] 0=coating over entire specimen.
1=coating on more than 50 percent of surface.
2=coating on less than 50 percent of surface.
3=little or no coating left.
[2] +=one or both specimens punctured.
[3] *P*=no pits greater than 6 mils.
[4] *D*=both specimens destroyed.

TABLE 5.—*Average and maximum penetrations of lead pipe exposed 2 years*

| Soil No. | Chemical lead [1] | | Tellurium lead [2] | | Antimonial lead [3] | |
|---|---|---|---|---|---|---|
| | Average penetration | Maximum penetration | Average penetration | Maximum penetration | Average penetration | Maximum penetration |
| | *Mils* | *Mils* | *Mils* | *Mils* | *Mils* | *Mils* |
| 51 | 0.68 | 40 | 1.32 | 54 | 1.14 | 56 |
| 53 | .24 | 24 | 0.27 | 16 | 0.27 | 12 |
| 55 | .41 | 24 | .37 | 32 | .21 | 28 |
| 56 | .23 | 38 | .41 | 68 | .34 | 42 |
| 58 | 1.70 | 62 | 1.83 | 55 | 1.58 | 52 |
| 59b | 0.39 | 28 | 0.25 | 18 | 0.22 | 10 |
| 60 | .20 | 21 | .16 | 33 | .11 | 10 |
| 61 | [4] 1.59 | 41 | [4] 1.32 | 35 | [4] 1.02 | 44 |
| 62 | 0.33 | 38 | 0.39 | 28 | 0.29 | 20 |
| 63 | .06 | 15 | .061 | 15 | .04 | 8 |
| 64 | .22 | 32 | .27 | 38 | .13 | 25 |
| 65 | .15 | 46 | .19 | 41 | .19 | 8 |
| 66 | .11 | 44 | .27 | 35 | .07 | 19 |
| 67 | 4.00 | 84 | 3.65 | 74 | 3.42 | 58 |
| 70 | 0.04 | 54 | 0.10 | 22 | 0.11 | 16 |

[1] Cu, 0.056 percent; Sb, 0.0011 percent; Bi, 0.002 percent.
[2] Cu, 0.082 percent; Sb, 0.0011 percent; Te, 0.043 percent.
[3] Cu, 0.036 percent; Bi, 0.016 percent; Sb, 5.31 percent.
[4] Individual specimens differ from the average by more than 50 percent.

The average penetration of the different varieties of lead in several of the soils approached, and in certain soils exceeded, the minimum thickness of the lead coating, namely, 0.50 mil. In fact, in four soils, Nos. 51, 58, 61, and 67, the average penetration of lead in 2 years did not differ greatly from the average thickness of the coating, 1.44 mils. Apart from considerations of over-all corrosion, the relatively high rate of pitting of the lead specimens in nearly all of the soils would undoubtedly cause perforation of a coating of any reasonable thickness within 2 years.

### 3. TINNED COPPER

Specimens of tinned copper tubes 1 inch in diameter and 14 inches long were exposed to corrosion in 15 soils in 1937. Although copper is highly resistant to corrosion in many soils, it corrodes appreciably in others. As tin is probably anodic to copper under all soil conditions, the corrosion of tin applied to copper as a metallic coating would be expected to protect copper cathodically in the same manner that the corrosion of zinc protects steel in galvanized materials.

The condition of the tinned copper specimens after 2 years is shown in table 6. As will be seen, the loss in weight of the tinned copper in most soils was less than that for unprotected copper, but the depths of the maximum pits on the coated specimens were usually greater.

A probable explanation of the deeper pits on the specimens of tinned copper is suggested by the work of Merica,[4] who found that copper was anodic to one of the copper-tin alloys formed in the process of tinning.

[4] P. D. Merica, Tech. Pap. BS **9**, (1917) T90.

TABLE 6.—*Loss of weight and depth of maximum penetration of tinned copper tubes and copper pipe exposed 2 years*

*M*=shallow metal attack as indicated by roughening of surface.
*P*=definite pitting but no pits greater than 6 mils.
*U*=unaffected by corrosion.
*S*=severe and uniform corrosion.
+=specimen punctured.

| Soil | | Tinned copper tube | | Deoxidized copper pipe | | Condition of coating [1] |
|---|---|---|---|---|---|---|
| No. | Type | Loss of weight | Penetration | Loss of weight | Penetration | |
| | | *oz/ft* [2] | *Mils* | *oz/ft* [2] | *Mils* | |
| 51 | Acadia clay | 0.18 | *P* | 0.40 | *M* | 2 |
| 53 | Cecil clay loam | .063 | *P* | .12 | *P* | 1 |
| 55 | Hagerstown loam | .064 | *M* | .14 | *P* | 0 |
| 56 | Lake Charles clay | .032 | 10 | .10 | *M* | 2 |
| 58 | Muck | .37 | 25 | .16 | *M* | 2 |
| 59 | Peat | .035 | *M* | ---- | ---- | 1 |
| 60 | Peat | 1.75 | 28 | 1.47 | 6(*S*) | 3 |
| 61 | Sharkey clay | 0.20 | [3, 4] 68+ | 0.059 | *P* | 1 |
| 62 | Susquehanna clay | [4] .029 | *P* | .16 | 5 | 1 |
| 63 | Tidal marsh | .44 | 6 | 1.13 | *M* | 1 |
| 64 | Docas clay | .18 | *P* | 1.41 | *S* | 1 |
| 65 | Alkali soil | .074 | *P* | 1.71 | *S* | 1 |
| 66 | Mohave sandy loam | .32 | 6 | 0.28 | 6 | 2 |
| 67 | Cinders | 12.03 | 60+ | 3.98 | 38 | 3 |
| 70 | Merced silt loam | 0.033 | *M* | ---- | ---- | 1 |

[1] 0=coating present over entire specimen.
1=coating on more than 50 percent of surface.
2=coating on less than 50 percent of surface.
3=little or no coating left.
[2] Individual measurements differ from the average by more than 50 percent.
[3] Hole in cap of one specimen.
[4] One specimen only.

## 4. PARKWAY CABLE

The parkway cable which was tested had a rubber-covered copper wire within a lead sheath. The sheath was wrapped with jute, and on this wrapper two spiral ribbons of zinc-coated steel were wound in opposite directions. These spirals were followed by an outer wrapper of bitumen-impregnated jute. Although most cables are laid in some form of conduit, this cable is usually laid directly in the soil.

Specimens were buried in 47 soils in 1923 and 1924. The last of these were removed from the corrosive soils in 1934 and their condition has been reported (see foot note 1). Table 7 shows the condition of the several protective layers. It will be noted that in all of the mildly corrosive soils the copper was completely protected throughout the 16 years of the test and would probably remain serviceable for many more years.

TABLE 7.—*Condition of parkway cable* [1] *exposed 16 years*

*G*=good.
*F*=fair.
*B*=bad.
*M*=metal attack.
*P*=pitted.
*R*=rusted.
*SR*=slightly rusted.
*VSR*=very slightly rusted.
*H*=1 or more holes.
*TW*=thin white corrosion product on lead sheet.
*W*=white corrosion product on lead sheet.

| Soil Number | Outer fabric | Inner fabric | Outer steel | Inner steel | Lead sheath |
|---|---|---|---|---|---|
| 2 | (2) | *G* | *M* | *M* | *TW* |
| 5 | *G* | *G* | *P* | *SR* | *TW* |
| 6 | *F* | *G* | *P* | *M* | *TW* |
| 7 | *G* | *G* | *P* | *VSR* | *W* |
| [3] 7 | *G* | *G* | *P* | *VSR* | *P* |
| 9 | *B* | *G* | *M* | *VSR* | *TW* |
| [3] 9 | *B* | *G* | *M* | *R* | *W* |
| 12 | (2) | *G* | *M* | *M* | *W* |
| 17 | *F* | *G* | *M* | *M* | *TW* |
| 26 | *F* | *G* | *M* | *VSR* | *TW* |
| 30 | *F* | *G* | *M* | *SR* | *TW* |
| 31 | *B* | *G* | *P* | *M* | *TW* |
| [3] 31 | *F* | *G* | *M* | *R* | *TW* |
| 36 | *F* | *G* | *M* | *M* | *TW* |
| 38 | *F* | *G* | *PH* | *R* | *TW* |
| 41 | *B* | *G* | *P* | *VSR* | *TW* |
| 47 | *G* | *G* | *M* | *VSR* | *W* |

[1] Data are for single specimens except for soils Nos. 7, 9, and 31.
[2] Removed in field.
[3] Second sample.

## IV. NONMETALLIC COATINGS

### 1. BITUMINOUS

Three types of bituminous coatings, all of the hot-dipped variety, were buried at 47 test sites in 1924—namely, No. 4, asphalt coating; No. 7, a coal-tar pitch coating; and No. 10, an asphalt coating reinforced with cotton fabric. The last inspection of these coatings was made in 1934, when the last sets were removed from the more corrosive soils. In the report [5] in which the condition of these coatings was described will be found data on the behavior of many types of coatings. The appearance and general condition of the coatings removed in 1939 from 16 sites were practically unchanged since the last inspection.

The coal-tar pitch dip coating, designated as No. 7, had a free-carbon content of 17 percent and a ring-and-ball softening point of 195° F. It was applied by twice dipping the pipe vertically into the coating bath, which was held at 250° to 260° F. The thickness of the coating was approximately 0.007 inch. Numerous rust spots appeared on the surface of the coating at nearly all test sites. The coating appeared to be brittle, and in many cases part of it could be brushed from the pipe.

The asphalt coating (No. 4) was prepared from the residuum from Mexican petroleum. The penetration of this material at 77° F, 100 g, 5 sec, was 20. The softening point (ring-and-ball method) was 185° F. The pipe was dipped twice in the bituminous material, which was held at approximately 350° F. The thickness of the coating varied between 0.008 and 0.016 inch. The appearance of this coating when removed from the soil was similar to that of coating No. 7.

[5] Kirk H. Logan, J. Research NBS **19,** 695 (1937) RP1058.

Neither coating was thick enough to prevent moisture reaching the pipe or to afford adequate protection, although the pits on the pipes having these coatings were not so deep (table 8) as on uncoated pipes. Such coatings are not now in general use on steel pipe, but a coal-tar dipped coating is commonly applied to cast-iron water pipe.

The reinforced asphalt coating, No. 10, consisted of a mixture of gilsonite and midcontinent asphalt reinforced by a woven cotton fabric applied in a lathe-type machine. The fabric passed through a tank of molten asphalt as it was wound spirally on the pipe. The thickness of the coating was approximately 0.08 inch. In a few of the soils this coating was apparently unchanged after 15 years' exposure. In most of the soils, however, the coating developed irregular cracks, the fabric rotted, and the bitumen appeared to have lost some of its oily constituents, so that it was friable. Rusting occurred on all of the pipes to which this coating was applied, but in 14 of the 16 soils the maximum depth of pitting was less than 25 mils.

Table 8 shows the maximum pit depths beneath the hot-dipped coatings in 16 soils. The last column shows the maximum pit depths on uncoated pipe, having a slightly greater area, after 17 years' exposure. This column shows clearly that the soils were not very corrosive, since in only one of them did the maximum pit depth exceed 100 mils. Two coated specimens having wall thicknesses of 0.145 inch exposed to Dublin clay were punctured, although the maximum pit depth on the uncoated pipe in this soil was only 50 mils.

TABLE 8.—*Maximum depth of penetration* [1] *on bitumen-coated and bare pipe exposed 15 years*

| Soil | | Coal-tar pitch (No. 7) | Asphalt (No. 4) | Asphalt, reinforced (No. 10) | Bare steel [2] |
|---|---|---|---|---|---|
| No. | Type | *Mils* | *Mils* | *Mils* | *Mils* |
| 2 | Bell clay | [4] 22 | | [4] 22 | 70 |
| 5 | Dublin clay adobe | [3] 145+ | 35 | [3] 145+ | 50 |
| 6 | Everett gravelly sandy loam | 15 | 14 | 15 | 21 |
| 7 | Maddox silt loam | | | [4] 22 | 68 |
| 9 | Genesee silt loam | 31 | 13 | [4] 14 | 76 |
| 12 | Hanford fine sandy loam | 12 | 19 | 20 | 81 |
| 17 | Keyport loam | [4] 30 | [4] 28 | [5] 11 | 42 |
| 24 | Merrimac gravelly sandy loam | 20 | 13 | [4] 20 | 33 |
| 26 | Miami silt loam | 38 | 17 | 11 | 44 |
| 27 | Miller clay | | | 27 | 76 |
| 31 | Norfolk sand | [4] 18 | | 30 | 52 |
| 35 | Ramona loam | 20 | 10 | 14 | 18 |
| 36 | Ruston sandy loam | 27 | 0 | [5] 23 | 62 |
| 38 | Sassafras gravelly sandy loam | 15 | 24 | 19 | 47 |
| 41 | Summit silt loam | [4] 30 | | [4] 13 | 105 |
| 47 | Unidentified silt loam | 106 | 10 | [4] 15 | 60 |

[1] Data for single specimen unless otherwise noted.
[2] Exposed 17 years.
[3] Pipe punctured.
[4] Average of the maximum pits on 2 specimens.
[5] Average of the maximum pits on 3 specimens.
[6] Average of the maximum pits on 5 specimens.

### 2. NONBITUMINOUS

#### (a) SPECIMENS EXPOSED 7 YEARS

The only information available descriptive of the coatings buried in 1932 was furnished by the manufacturers and is given below.

Coating *B*.—A synthetic rubber, stated to be an olefin polysulfide reaction product, was exposed in the form of sheets 10 by 5 by ¼ inches. Subsequently, a process was developed which permitted application of this material to pipes. Specimens coated by this process were exposed in 1939 and inspected in 1941. The condition of these coatings will be described in a later report.

Coating *C*.—Two coats of vitreous enamel, one of which was acid-resisting. Thickness, 14 mils.

Coating *D*.—First coat, 23-percent solution of a rubber derivative in xylene; second and third coats, 30-percent solution of the rubber derivative in xylene; fourth coat, 20-percent solution of the rubber derivative in a mixture of turpentine and mineral spirits. Five percent of the solids was carbon black. Thickness, 10 mils.

Coating *E*.—Two applications of paint which differed in color. Neither the kind of pigment nor the kind of vehicle was specified. Thickness, 5 mils.

Coating *F*.—A semiplastic compound, which was applied cold with a brush, consisting of 4½ parts of treated cashew-nutshell oil, 3 parts of asbestos fiber, and 3½ parts of mineral turpentine substitute. Thickness, 6 mils.

Coating *G*.—A hard-rubber compound, containing rubber, sulfur, and an accelerator, cured to a bone-hard condition. Thickness, 90 mils.

Coating *H*.—A highly loaded hard-rubber stock which contained 30 percent of magnesium carbonate and approximately 15 percent of "white substitute." Thickness, 100 mils.

Coating *J*.—A synthetic resin varnish baked at 425° F for 30 minutes.

Coating *K*.—A paint containing highly chlorinated rubber, dissolved in a suitable solvent, to which may have been added drying oils, pigments, quartz meal, or carborundum. This coating was applied in Germany to pipe 1 inch in outside diameter. Thickness, 6 mils.

Coating *W*.—An experimental coating prepared as follows: The pipe was primed with a china-wood oil varnish containing zinc chromate and basic lead chromate and baked at 200° F for ½ hour. A top coat of dehydrated china-wood oil, containing powdered mica and a catalyst was molded on the pipe and heated to 200° F for 3 hours. Thickness, 170 mils.

The condition of the specimens after exposure to the soil for 7 years is shown in table 9.

TABLE 9.—*Condition of miscellaneous nonmetallic coatings after exposure for 7 years*

*E*=ends corroded. *G*=ends rusted. *H*=pipe punctured=145+ mils. *M*=metal attack, pipe roughened by corrosion. *R*=rusted. *P*=definite pitting, but no pits greater than 6 mils. *U*=no corrosion. +=pipe punctured after 5 years.

[Figures indicate depths of maximum pits in mils]

| Soil No. | Soil Type | Specimen number | Porcelain enamel (*C*) | Rubber paint (*D*) | Paint (*E*) | Cashew-nut-oil-asbestos fiber (*F*) | Hard rubber (*G*) | Loaded hard rubber (*H*) | Synthetic resin (*J*) | Chlorinated rubber paint (*K*) | China wood oil-mica compound (*W*) | Maximum pit on uncoated low-carbon steel pipe (*N*) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 51 | Acadia clay | 1 | *UE* | 30 | 40 | *R* | | | | | *M* | 116 |
| | | 2 | 55(*E*) | 90 | 82 | *R* | | | | | *R* | *H*+ |
| 53 | Cecil clay loam | 1 | *U* | *M* | *P* | *R* | | | *R* | | *M* | 62 |
| | | 2 | *U* | *R* | 15 | *R* | | | *R* | | 17 | 46 |
| 55 | Hagerstown loam | 1 | *M* | *M* | *M* | *R* | | | | | *R* | 52 |
| | | 2 | *R* | *M* | *M* | *R* | | | | | *R* | 62 |
| 56 | Lake Charles clay | 1 | *E* | 27 | *H* | *M* | | | | *R* | *R* | 96 |
| | | 2 | *E* | 25 | 55(*E*) | *M* | | | | | *M* | *H* |
| 58 | Muck | 1 | 41(*E*) | 60 | *H* | 60 | | | | | *R* | 139 |
| | | 2 | 52(*E*) | 66 | 63 | 46 | | | | | 58 | 79 |
| 59 | Peat | 1 | *U* | 14 | 15 | *U* | *UG* | *U* | | | *R* | 38 |
| | | 2 | *U* | *R* | 14 | *U* | *UG* | *U* | | | *R* | 21 |
| 60 | ....do | 1 | *UE* | 19 | 17 | *M* | *UG* | *U* | | | *R* | 10 |
| | | 2 | *UE* | 42 | 23 | *R* | *UG* | *U* | | | *R* | 23 |
| 61 | Sharkey clay | 1 | *UE* | *R* | 15 | *R* | | | | | *R* | 76 |
| | | 2 | *U* | *R* | 25 | *R* | | | | | *U* | 50 |
| 62 | Susquehanna clay | 1 | *R* | *R* | 24 | *R* | | | | | *M* | 83 |
| | | 2 | *U* | *R* | 18 | *R* | | | | | *M* | 58 |
| 63 | Tidal marsh | 1 | *UE* | 21 | 15 | 70 | | | | | *M* | 78 |
| | | 2 | *UE* | *M* | 22 | *M* | | | | | *M* | 61 |
| 64 | Docas clay | 1 | *U* | 45 | *H* | *M* | *UG* | *U* | 80 | 32 | *R* | *H*+ |
| | | 2 | *UE* | 17 | *H* | 20 | *U* | *U* | 50 | | *M* | *H*+ |
| 65 | Alkali soil | 1 | *UE* | 20 | *H* | 10 | *UG* | *UE* | | | *R* | 90 |
| | | 2 | *ME* | *M* | 45 | *M* | *UG* | *UG* | | | *R* | 76 |
| 66 | Mohave sandy loam | 1 | *UE* | 19 | 100 | *M* | *UG* | *UG* | | | *R* | *H*+ |
| | | 2 | *UE* | 30 | 70 | *P* | *UG* | *UG* | | | *R* | *H*+ |
| 67 | Cinders | 1 | *UE* | *M* | 63 | 21 | *UG* | *U* | *H* | *M* | *R* | 100 |
| | | 2 | *UE* | *H* | *H* | *M* | *UG* | *UG* | *H* | | *R* | *H*+ |

Practically no corrosion was found on the specimens to which coatings *C*, *G*, or *H* were applied. Rusting was fairly general on pipes beneath the *D*, *E*, *F*, and *W* coatings. These coatings blistered in several of the soils, adhered poorly, and became brittle.

The sheets designated as specimen *B* became brittle and hardened during exposure. When bent slightly, they cracked in a few instances.

#### (b) SPECIMENS EXPOSED 2 YEARS

Nearly all of the nonmetallic coatings buried in 1937 were of the phenol-formaldehyde (bakelite) type, and were applied to pipe 1½ inches in diameter. The descriptions of the coatings follow:

Coating *L*.—Two coats of a bakelite varnish followed by two coats of another type of bakelite varnish, each coat being baked after spraying. Thickness, 7 mils.

Coating $M_1$.—Two coats of a bakelite primer containing zinc chromate followed by two coats of aluminum paste in bakelite varnish. Each coat was sprayed on and allowed to dry overnight. Thickness, 4 mils.

Coating $M_2$.—The same as coating $M_1$, except that it was applied to 2½- by 12-inch plates instead of to pipe. Thickness, 3 mils.

Coating *N*.—A double layer of Bakelite-treated asbestos tape over which was sprayed a Bakelite-aluminum enamel. Thickness, 32 mils.

Coating *P*.—A fabric coated on one side with Koroseal to an over-all thickness of 0.03 inch. The fabric was wrapped spirally on the pipe under tension with the fabric next to the metal and then painted with two coats of Koroseal solution applied hot. Thickness, 33 mils.

Because of the short period of exposure, only a brief summary of the condition of the specimens is given in table 10.

In the group of coatings exposed for 2 years the Bakelite coating, *L*, consisting of several coats of Bakelite varnish, each coat being baked on, afforded the most complete protection. The air-dried Bakelite coatings blistered somewhat and permitted some rusting, but severe corrosion under these coatings occurred only in cinders.

TABLE 10.—*Summary of condition of pipe and coatings exposed 2 years*

[Figures in the table refer to the number of test sites]

| Coating symbol | Pipe | | | | Coating blistered |
|---|---|---|---|---|---|
| | Unaffected | Rusted | Roughened | Pitted | |
| *L* | 5 | [2] 9 | 0 | [1] 1 | 0 |
| $M_1$ | 2 | 10 | 0 | 3 | 13 |
| $M_2$ | 0 | 4 | 6 | 5 | 15 |
| *N* | 5 | 5 | 3 | 2 | 0 |
| *P*[3] | 0 | 1 | 2 | 2 | 0 |

[1] Exposed to cinders.
[2] Condition possibly due to injury to coating in handling.
[3] Poor bond between pipe and coating.

## V. CONCLUSIONS

The protection afforded by zinc coatings in soils depended on the thickness of the coating and was not appreciably affected by the kind of ferrous material to which the coating was applied. The superior protection which was provided by a 3-ounce zinc coating specially applied, as compared with a commercial coating of the same weight, may indicate that uniformity of coating is important.

Lead coatings applied to iron and steel have not proved adequate for protection underground. Since the potential of lead is cathodic to that of iron, lead cannot protect iron or steel cathodically in the manner that these metals are protected by a zinc coating. As the rate of corrosion of lead is appreciable under many soil conditions, a continuous layer of lead isolating steel from the environment cannot usually be maintained.

Tin-coated copper is susceptible to corrosion in soils which are corrosive to copper. In fact, in some soils the rate of pitting of copper appeared to be accelerated. Under certain conditions one or more tin-copper alloy layers may be cathodic to copper, a condition which would accelerate corrosion.

After exposure to soils for 15 years, two hot-dipped asphalt and coal-tar coatings were found to have failed, as indicated both by pitting of the underlying metal and deterioration of the coating.

Of the group of experimental coatings exposed 7 years, a vitreous-enamel coating and two hard-rubber coatings afforded complete protection.

In the group of coatings exposed 2 years, a Bakelite coating consisting of several coats of Bakelite varnish, each coat being baked on, afforded the most satisfactory protection. The air-dried Bakelite coatings blistered somewhat and permitted some rusting, but severe corrosion under these coatings occurred only in cinders.

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The preparation of the specimens, the measurements of corrosion, and the calculation of the results were made under the supervision of Melvin Romanoff. The writer also acknowledges the assistance rendered by David Fickle and Richard F. Thomas in these various operations.

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# ELASTIC PROPERTIES OF SOME ALLOY CAST IRONS

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ABSTRACT

Transverse-strength properties were determined on 1.2-in. diameter test bars made from three types of alloy iron heated, before casting, to the maximum temperatures of 1,400°, 1,500°, 1,600°, and 1,700° C. The bars were vertically cast, bottom-poured in green-sand molds, at a temperature of 100°, 150°, 200°, or 250° C above the liquidus. Total, plastic, and elastic deflection, modulus of rupture, relative moduli of elasticity, and total, plastic, and elastic resilience were determined, and the microstructure of the test bars was examined. Comparative values of four different relative moduli of elasticity relating to the same test bars but calculated by different methods are discussed. Comparison of transverse test properties of alloy and plain carbon irons is made.

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## I. INTRODUCTION

A knowledge of the elastic properties of cast iron is important for its use in structural parts, such as piston rings, cylinder liners, etc. The present investigation is an extension to three types of alloy cast iron of a previous study [1] [1] of the elastic properties of three types of plain cast iron. The same procedure of melting and casting and the same methods of testing as those described in the previous paper were employed.

## II. SCOPE OF INVESTIGATION

The research consisted in making transverse test bars 1.2 in. in diameter and 21 in. in length and testing these for transverse strength,

[1] Figures in brackets indicate the literature references at the end of this paper.

deflection, Brinell hardness, and microstructure. A universal testing machine of the hydraulic type of 50,000 lb capacity was used for transverse tests.

### 1. METALS USED

Three types of alloy cast irons were selected for this investigation: Iron *L*, a nickel-molybdenum high-silicon iron; iron *M*, a nickel-molybdenum-chromium, low-manganese, medium-silicon iron; and iron *N*, a nickel-molybdenum-chromium, high-manganese, high-silicon iron. The stock pig irons, *B* and *C* (table 1), used in the previous investigation were also employed in the present study. Stock iron *B* was employed in making heats of irons *M* and *N*, while stock iron *C* was employed for making heats of iron *L*.

TABLE 1.—*Chemical analysis of stock pig irons*

| Iron | Total carbon | Silicon | Manganese | Phosphorus | Sulfur |
|---|---|---|---|---|---|
| | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* |
| *B* | 3.79 | 1.40 | 0.63 | 0.181 | 0.062 |
| *C* | 3.44 | 2.43 | .77 | .395 | .050 |

## III. FOUNDRY PROCEDURE

The foundry technique was similar to that used in the previous investigation.

### 1. PREPARATION OF MOLD

Molds for transverse test bars were made of a mixture of 8 parts of molding sand and 1 part of sea coal, tempered to approximately 7 percent of moisture. The mold cavities were faced with nongraphitic carbonaceous material of commercial origin.[2] The bars were bottom-poured in groups of four in a three-part vertical flask, and each flask contained two groups, that is, eight bars.

### 2. MELTING

Charges of 230 to 250 lb of iron, in a commercial magnesia crucible, were melted in a high-frequency induction furnace of the tilting type.

When the charge of stock iron was melted, the metal was slagged off and necessary additions were made. First, open-hearth ingot iron was charged into the melt, and then other elements were added. Nickel was added in the form of nickel shot, whereas silicon, manganese, chromium, and molybdenum were added in the form of their respective ferro-alloys. The major portion of the ferro-silicon (about two-thirds of the total amount) was added after all other additions had been made. The elapsed time between the last addition of ferro-silicon and the pouring of a group of transverse test bars varied from about 4 minutes to 1 hour, depending upon the maximum heating and pouring temperatures employed.

### 3. TEMPERATURES USED AND THEIR MEASUREMENT

Each melt was heated to a predetermined maximum temperature of 1,400°, 1,500°, 1,600°, or 1,700° C (2,550°, 2,730°, 2,910°, or 3,090° F).

[2] Approximate analysis:

| | |
|---|---|
| Volatile matter | 4.0% |
| Fixed carbon | 74.0% |
| Ash | 22.0% |

Each group of four bars was cast as a unit at a predetermined pouring temperature of 100°, 150°, 200°, or 250° C (210°, 300°, 390°, or 480° F), above the liquidus temperature of the iron investigated. Temperatures up to 1,600° C (2,910° F) were measured by a platinum to platinum-rhodium thermocouple and temperatures above 1,600° C (2,910° F) by an optical pyrometer. To determine the corrections to be applied to the readings of the optical pyrometer under these conditions, observations were taken simultaneously with both the thermocouple and the optical pyrometer in the temperature range of 1,400° to 1,550° C (2,550° to 2,820° F). These corrections were then plotted as a function of the temperature, and the curve extended up to 1,700° C (3,090° F). The thermocouple assembly used in measuring temperatures of molten cast iron was described in a previous paper [2].

## IV. GENERAL REMARKS CONCERNING COMPOSITION OF TRANSVERSE TEST BARS

After completing the transverse tests, the bars were sampled for chemical analysis. The analytical data are summarized in table 2. Since the variation in pouring temperature did not appreciably affect the composition of heats, these data refer to the heats made at different maximum heating temperatures, the pouring temperature being constant.

The most consistent results were obtained with iron *L*, whereas a considerable fluctuation in composition was noticed for irons *M* and *N*, particularly in the content of silicon.

TABLE 2.—*Chemical analysis of cast iron bars of irons L, M, and N, heated to different maximum temperatures and poured at 1,350° C*

| Iron | Maximum heating temperature | Chemical analysis | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Carbon | | | Si | Mn | P | S | Ni | Cr | Mo |
| | | Total | Graphitic | Combined | | | | | | | |
| | °C | % | % | % | % | % | % | % | % | % | % |
| *L* | 1,400 | 3.38 | 2.82 | 0.56 | 2.35 | 0.63 | 0.39 | 0.05 | 1.04 | ..... | 0.72 |
| | 1,500 | 3.33 | 2.79 | .54 | 2.34 | .70 | .39 | .05 | 1.05 | ..... | .76 |
| | 1,600 | 3.33 | 2.75 | .58 | 2.39 | .71 | .39 | .04 | 1.08 | ..... | .71 |
| | 1,700 | 3.23 | 2.62 | .61 | 2.32 | .72 | .40 | .04 | 1.01 | ..... | .75 |
| *M* | 1,400 | 3.16 | 2.43 | .73 | 1.84 | .43 | .14 | .03 | 1.57 | 0.27 | .98 |
| | 1,500 | 3.12 | 2.37 | .75 | 2.02 | .45 | .15 | .03 | 1.60 | .24 | .77 |
| | 1,600 | 3.04 | 2.33 | .71 | 2.02 | .47 | .14 | .04 | 1.59 | .24 | .76 |
| | 1,700 | 3.14 | 2.42 | .72 | 2.23 | .53 | .15 | .04 | 1.67 | .28 | .86 |
| *N* | 1,400 | 2.83 | 2.10 | .73 | 2.59 | .89 | .13 | .04 | 1.24 | .21 | 1.20 |
| | 1,500 | 3.06 | 2.46 | .60 | 2.76 | 1.04 | .13 | .04 | 1.27 | .21 | 1.09 |
| | 1,600 | 2.82 | 2.13 | .69 | 2.75 | .99 | .13 | .04 | 1.23 | .21 | 1.22 |
| | 1,700 | 2.88 | 2.16 | .72 | 2.70 | .99 | .12 | .04 | 1.24 | .21 | 1.17 |

## V. DETERMINATION OF TRANSVERSE TEST PROPERTIES

The term "elastic properties" in this paper connotes those complex properties that determine the behavior of cast iron under load and, more specifically, under transverse bending load.

## 1. DEFLECTION

It is well known that the determination of the elastic properties of cast iron is complicated by the fact that even low stresses produce plastic as well as elastic deformation.

The method used by the National Bureau of Standards to measure deflection in cast-iron bars has been described elsewhere [1, 3]. A brief outline for the reader's convenience is as follows: As shown in figure 1, a rubber band, *B*, is stretched tightly along the length of the bar, *A*, and is held in position by two clamps, *C*. Metal strips on the inner surface of the clamps keep the rubber band near to, but not in contact with, the surface of the bar at all times. The 18-in. spacing between the two clamps is the same as that between the supports for the bar in the testing machine. A small piece of paper, *D*, is cemented to the surface of the bar midway between the clamps, *C*, and the upper edge of this piece of paper serves as a reference mark.

In conducting the test, the bar is placed in the testing machine (fig. 2) and a micrometer-telescope, *E* (fig. 1), mounted at a distance of 20 in. from the bar, is used to measure the distance between the lower edge of the rubber band and the reference mark. The rubber band clamped to the bar at the two supports remains practically straight, so that the displacement of the reference mark relative to the band is a measure of the center deflection of the loaded bar. A similar measurement after the load has been removed indicates the permanent set at the center.

After a test bar, *A*, was mounted in the testing machine and adjusted until the rubber band, *B*, was in the horizontal plane through the neutral axis of the bar, a load of 50 lb was applied and the distance between the lower edge of the rubber band and the reference mark was determined and used as the zero reading. This load was sufficient to seat the bar firmly. The deflection of the bar was then measured as it was loaded in a series of steps of 100 or 200 lb each. After the load had reached 1,000 lb, each application of load was followed by unloading to the original 50-lb load, and the permanent set in the unloaded bar was determined. The total deflection at the breaking load and the "set" of each bar under increasing step loadings were determined, and the elastic deflection was taken as the difference between the total and the plastic deflection for each load. In each group of four bars (poured at the same temperature), two were tested by the step loading and unloading method while the two companion bars were progressively loaded to failure, without unloading between successive loads. No difference in the breaking loads and the load-deflection curves, which could be ascribed to the mode of loading, was observed.

As shown in table 3, there is no definite relation between the ultimate total, as well as the ultimate elastic deflections and maximum heating and pouring temperatures. The ultimate total, elastic, and plastic deflections are considerably higher for irons *M* and *N* than for iron *L*. From table 3 and the data obtained in the previous investigation it may be noted that the ultimate total, elastic, and plastic deflections for plain carbon irons (irons *A*, *B*, and *C*) and alloy irons (irons *L*, *M*, and *N*) range as shown in table 4.

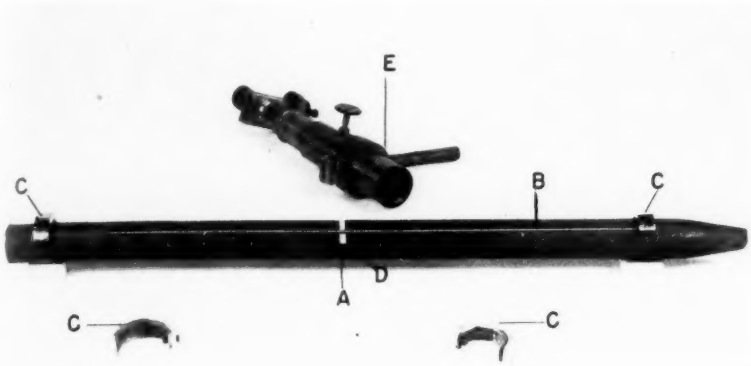


FIGURE 1.—*Apparatus for measuring deflection of cast-iron bars under transverse loading.*

*A*, Cast-iron bar; *B*, Rubber band; *C*, Clamps; *D*, Reference mark; *E*, Micrometer telescope.

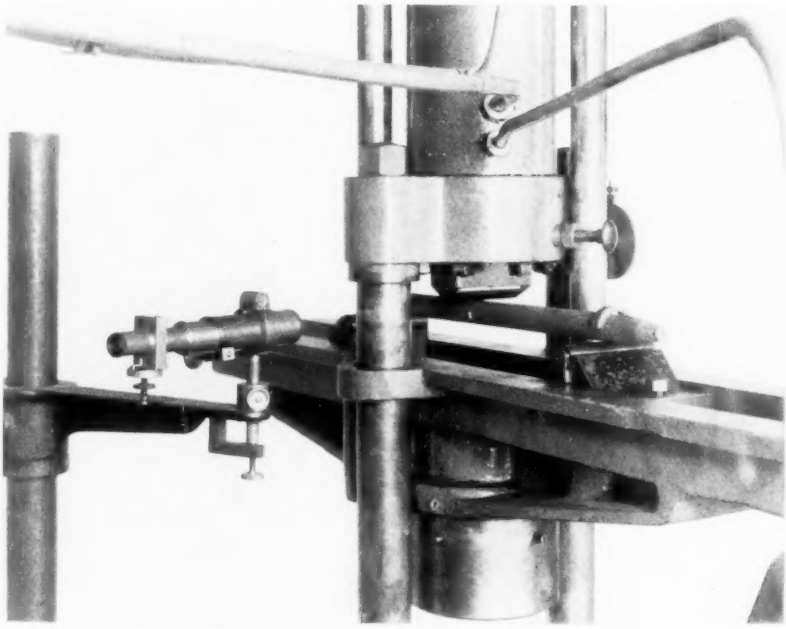

FIGURE 2.—*Test bar mounted in the 50,000 lb testing machine.*

Micrometer-telescope support is independent of the testing machine.

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TABLE 3.—*Transverse breaking strength, modulus of rupture and ultimate total and elastic deflections* [1]

| Iron | Pouring temperature | Transverse breaking strength of metal heated to— | | | | Modulus of rupture of metal heated to— | | | | Ultimate total deflection of metal heated to— | | | | Ultimate elastic deflection of metal heated to— | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1,400° C | 1,500° C | 1,600° C | 1,700° C | 1,400° C | 1,500° C | 1,600° C | 1,700° C | 1,400° C | 1,500° C | 1,600° C | 1,700° C | 1,400° C | 1,500° C | 1,600° C | 1,700° C |
| | °C | lb | lb | lb | lb | lb/in.² | lb/in.² | lb/in.² | lb/in.² | in. | in. | in. | in. | in. | in. | in. | in. |
| L | 1,400 | | 2,440 | 2,500 | 2,640 | | 64,800 | 68,700 | 69,900 | | 0.22 | 0.24 | 0.22 | | 0.20 | 0.20 | 0.19 |
| | 1,350 | 2,630 | 2,520 | 2,650 | 2,600 | 69,900 | 66,800 | 70,300 | 68,900 | 0.24 | .21 | .24 | .21 | 0.20 | .18 | .21 | .18 |
| | 1,300 | 2,730 | 2,620 | 2,760 | 2,830 | 72,300 | 69,600 | 73,100 | 75,000 | .24 | .22 | .26 | .22 | .21 | .19 | .21 | .18 |
| | 1,250 | 2,310 | 2,630 | | 2,640 | 61,300 | 69,800 | | 72,700 | .22 | .21 | | .22 | .19 | .19 | | .19 |
| M | 1,450 | | 3,390 | 3,030 | 2,980 | | 89,900 | 80,400 | 78,900 | | .36 | .30 | .31 | | .26 | .23 | .23 |
| | 1,400 | 3,190 | 3,180 | 3,250 | 3,111 | 84,600 | 84,500 | 86,200 | 82,000 | .32 | .31 | .33 | .31 | .24 | .24 | .24 | .23 |
| | 1,350 | 3,350 | 3,140 | 3,470 | 3,290 | 88,900 | 83,200 | 92,100 | 87,200 | .34 | .30 | .36 | .33 | .24 | .23 | .26 | .25 |
| | 1,300 | 3,430 | 3,360 | 3,140 | 3,220 | 91,100 | 89,200 | 83,300 | 85,500 | .32 | .35 | .33 | .31 | .24 | .26 | .24 | .24 |
| | 1,250 | 3,340 | | | | 88,800 | | | | .34 | | | | .24 | | | |
| N | 1,450 | | 3,200 | 3,500 | 3,420 | | 85,000 | 92,900 | 90,800 | | .31 | .33 | .30 | | .24 | .25 | .23 |
| | 1,400 | 3,400 | 3,290 | 3,690 | 3,520 | 90,200 | 87,300 | 97,800 | 91,600 | .32 | .31 | .34 | .30 | .24 | .25 | .26 | .23 |
| | 1,350 | 3,510 | 3,430 | 4,060 | 4,030 | 93,200 | 91,100 | 107,700 | 106,900 | .32 | .33 | .37 | .34 | .24 | .25 | .28 | .27 |
| | 1,300 | 3,550 | 3,610 | 3,960 | 3,720 | 94,100 | 95,800 | 105,200 | 98,700 | .32 | .33 | .37 | .33 | .25 | .26 | .28 | .25 |

[1] The values presented in this table are averages of values for a group of 4 bars cast at the same pouring temperature.

TABLE 4.—*Ultimate deflections and proportion of plastic deflection to the total deflection at fracture for alloy and plain carbon cast irons*

| | Alloy irons | | | Plain carbon irons | | |
|---|---|---|---|---|---|---|
| | *L* | *M* | *N* | *A*[1] | *B*[1] | *C*[1] |
| | Ultimate deflection (inches) | | | | | |
| Total | 0.21 to 0.26 | 0.30 to 0.36 | 0.30 to 0.37 | 0.18 to 0.24 | 0.25 to 0.30 | 0.20 to 0.28 |
| Elastic | .18 to .21 | .23 to .26 | .23 to .28 | .15 to .18 | .17 to .19 | .16 to .21 |
| Plastic | .02 to .05 | .07 to .10 | .07 to .09 | .03 to .06 | .08 to .11 | .04 to .07 |
| | Proportion of plastic deflection to the total deflection at fracture (percent) | | | | | |
| | 9 to 19 | 23 to 28 | 23 to 24 | 17.0 to 25.0 | 32.0 to 37 | 20.0 to 25.0 |

[1] Iron *A* contains: Total C, 3.44 percent; Si, 1.40 percent; Mn, 0.15 percent; P, 0.46 percent; S, 0.02 percent. Chemical analyses of irons *B* and *C* are given in table 1.

Table 4 indicates that the ultimate elastic deflections obtained for alloy iron *L* are practically equivalent to those of plain carbon irons *A*, *B*, and *C*. However, the total plastic deflection of alloy iron *L* was somewhat inferior to those of the plain carbon irons *B* and *C*. The highest values of total and elastic deflections were observed for alloy irons *M* and *N*, whereas the highest values of plastic deflection were associated with plain carbon iron *B*. If the proportion of plastic deflection to the total deflection at fracture is considered as an index of rigidity of cast iron, then iron *L* is the most rigid and iron *B* the least rigid. The rigidities of irons *M*, *N*, *A*, and *C* are almost equal.

All the results of this investigation confirm the conclusions drawn from the previous study [1] with regard to the total, plastic, and elastic deflection curves obtained by the method just described, that is, the total and plastic deflection curves are continuous curves inclining progressively toward the deflection axis. The elastic-deflection curve is a straight line in its lower portion, but at approximately three-fifths of the breaking load, it inclines toward the deflection axis. Typical load-deflection curves for the irons investigated are shown in figure 3. All transverse tests were made with a universal testing machine of the hydraulic type of 50,000 lb capacity, the rate of loading corresponding to 0.12 in. per minute travel of the free cross head of the testing machine. According to an ASTM specification,[3] the error for loads within the loading range of a testing machine shall not exceed 1 percent. Since the error of the machine for loads smaller than 1,000 lb exceeds 1 percent, only the total deflections were measured at the loads of 400, 600, 800, 1,000 lb, etc., and no plastic and elastic deflections were determined at loads less than 1,000 lb. Consequently, curves corresponding to the loads below 1,000 lb are not shown in figure 3. It may be stated, however, that in most of the cases observed the initial portions of the load-total deflection diagrams (for loads of 200 to 1,000 lb) appeared to be continuous smooth curves. This was particularly true of the alloy irons.

### 2. TRANSVERSE STRENGTH

It may be noted in table 3 that the transverse breaking strengths for iron *L* range from 2,310 to 2,830 lb/in.$^2$, iron *M* from 2,980 to

[3] Specification E4-36, Am. Soc. Testing Materials, Standards, pt. 1, Metals, p. 774 (1939).

3,470 lb/in.$^2$, and iron *N* from 3,200 to 4,060 lb/in.$^2$ In accordance with ASTM classification,[4] these irons would fall in the following classes: Iron *L*, 35–40; iron *M*, 50; and iron *N*, 50–60 or higher.

The higher strength of irons *M* and *N*, as compared with iron *L*, probably is due to their higher nickel content and more particularly to the presence of chromium. The low carbon, high manganese, and molybdenum contents of iron *N* appear to account for the higher strength as compared to iron *M*. This high strength was obtained in spite of the larger silicon content present in iron *N*. As shown in figure 4, the maximum heating temperature had no effect on the transverse strength of irons *L* and *M*, but the strength of iron *N* was found to be somewhat higher for the maximum heating temperature of 1,600° and 1,700° C (2,910° and 3,090° F) than for 1,400° and 1,500° C (2,550° and 2,730° F). In general, however, lower pouring tem-

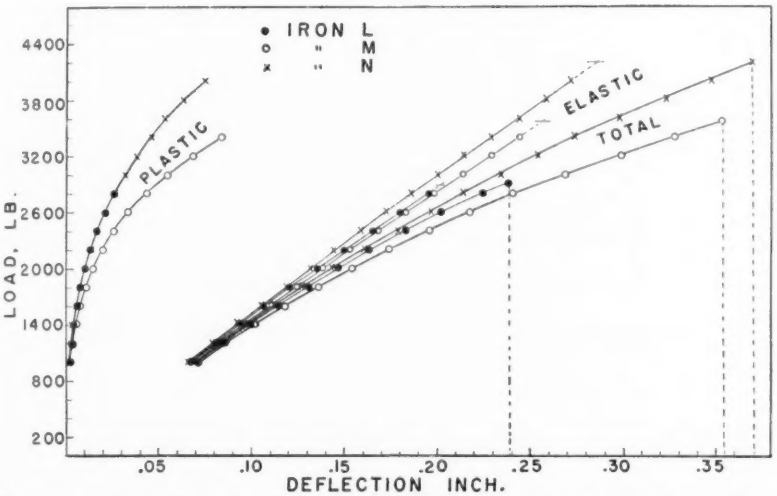


FIGURE 3.—*Typical plastic-, elastic-, and total-deflection curves of irons L, M, and N.*

peratures, ranging from 100° to 150° C above the liquidus, tend to produce stronger irons.

It is very probable that the effect of maximum heating temperature on the physical properties of these irons was, to a certain degree, masked by the variation in chemical analysis and the time of making the last addition of silicon to the melt before pouring.

In comparing the transverse strengths of alloy irons with those of plain carbon irons *A*, *B*, and *C*, previously studied, it may be stated that the strongest plain carbon iron, *A*, is equivalent to the nickel-molybdenum iron, *L*. The beneficial effect of increasing the maximum heating temperature on the transverse strength was more pronounced for plain carbon irons than for alloy irons.

The effect of pouring temperature for both types of iron was about the same, that is, the transverse strength tended to increase with a decrease of pouring temperature.

[4] Specifications A 48-36, Am. Soc. Testing Materials, Standards, pt. 1, Metals, p. 482 (1939).

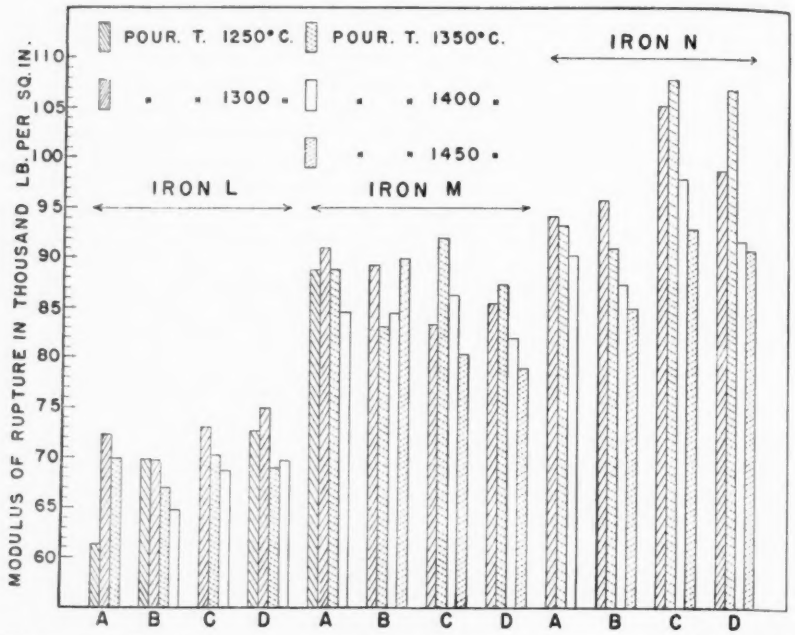


FIGURE 4.—*Effect of maximum heating and pouring temperatures on the modulus of rupture of irons L, M, and N.*

Maximum heating temperatures *A*, 1,400° C; *B*, 1,500° C; *C*, 1,600° C; *D*, 1,700° C.

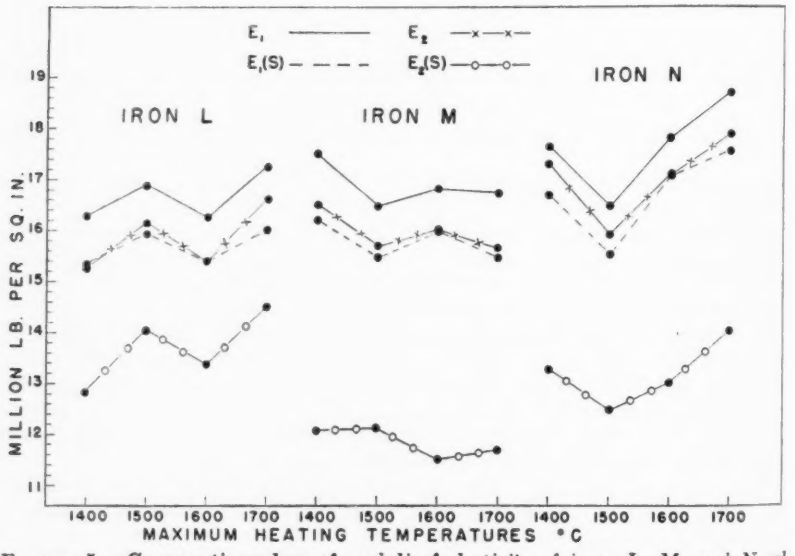


FIGURE 5.—*Comparative values of moduli of elasticity of irons L, M, and N calculated by different methods.*

### 3. RELATIVE MODULUS OF ELASTICITY

In the American Foundrymen's Association Cast Metals Handbook, the term "modulus of elasticity," as applied to gray iron, generally means the relative stiffness of the irons under the particular conditions of loading. In the previous and in this investigation, the term "relative modulus of elasticity" is used in place of "modulus of elasticity." Different relative moduli of elasticity were calculated from the data obtained in this investigation, as follows:

$E_1$=Relative modulus computed by simple beam theory from slope of straight line through elastic load-deflection curve at 1,200 lb.

$E_1(S)$=Relative modulus computed from slope of secant to load-total deflection curve at 1,200 lb.

$E_2$=Relative modulus computed from slope of secant through elastic load-deflection curve at failure.

$E_2(S)$=Relative modulus computed from slope of secant to load-total deflection curve at failure.

The average values of different moduli of elasticity of irons *L*, *M*, and *N* obtained at different maximum heating and pouring temperatures are given in table 5. In order to compare the different moduli of elasticity, values corresponding to 1,350° C pouring temperature are plotted for different maximum heating temperatures (fig. 5).

From the figures it may be observed that the relative moduli of elasticity are arranged according to their numerical values in the following order: the values for $E_1$ are the highest and for $E_2$ ($S$) the lowest; $E_2$ and $E_1$ ($S$) values are comparatively close together; and in general, there is a small difference between $E_1$, $E_2$, and $E_1$ ($S$) values, but $E_2$ ($S$) is considerably lower. When a similar plotting is made for four different moduli of elasticity of the plain carbon irons, *A*, *B*, and *C*, previously investigated, the results obtained are similar to those just described for the alloy irons.

As has been mentioned, in the determination of the relative moduli of elasticity, $E_1$ and $E_2$, it is necessary to define complete load-deflection curves by means of stepwise loading and unloading. This is a rather tedious procedure and requires a great deal of time. It was thought, therefore, that the determination of the relative modulus of elasticity would be simplified if a definite relation could be established between the relative modulus of elasticity, $E_1$, and the relative secant modulus of elasticity, $E_1$ ($S$), computed for the same load. With this thought in mind, calculations were made to determine the ratios between moduli $E_1$ and $E_1$ ($S$) for all transverse test bars investigated, the load of 1,200 lb being adopted as a minimum load for these calculations. The data obtained indicate that the $E_1/E_1(S)$ ratios were around 1.060.

It seems, therefore, that for practical purposes for the irons investigated, it may be assumed that

$$E_1=E_1\,(S)\times 1.060.$$

It has been found, however, that this assumption can be applied only to the group of alloy irons under present study. When similar calculations were made for the plain carbon irons, *A*, *B*, and *C* previously reported, it was observed that the $E_1/E_1(S)$ ratios were quite different and extremely irregular.

TABLE 5.—*Relative moduli of elasticity* ($lb/in.^2 \times 10^6$)

| Iron | Pouring temperature | Modulus of elasticity, $E$, at load of 1,200 lb, of metal heated to— | | | | Secant modulus of elasticity at load of 1,200 lb, $E_1(S)$, for metal heated to— | | | | Ultimate modulus of elasticity, $E_2$, for metal heated to— | | | | Ultimate secant modulus of elasticity, $E_3(S)$, for metal heated to— | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1,400° C | 1,500° C | 1,600° C | 1,700° C | 1,400° C | 1,500° C | 1,600° C | 1,700° C | 1,400° C | 1,500° C | 1,600° C | 1,700° C | 1,400° C | 1,500° C | 1,600° C | 1,700° C |
| | °C | | | | | | | | | | | | | | | | |
| *L* | 1,400 | ..... | 16.25 | 15.85 | 17.68 | ..... | 15.14 | 14.81 | 16.54 | ..... | 14.92 | 15.14 | 16.71 | ..... | 12.76 | 13.06 | 14.27 |
| | 1,350 | 16.27 | 16.90 | 16.24 | 17.25 | 15.35 | 15.91 | 15.41 | 16.00 | 15.26 | 16.13 | 15.39 | 16.62 | 12.83 | 14.05 | 13.39 | 14.51 |
| | 1,300 | 16.56 | 17.40 | 16.15 | 17.55 | 15.61 | 16.29 | 15.19 | 16.54 | 15.49 | 16.12 | 15.15 | 16.57 | 13.00 | 14.18 | 12.92 | 14.47 |
| | 1,250 | 16.80 | 17.81 | ..... | 18.00 | 15.86 | 16.39 | ..... | 16.97 | 15.35 | 16.83 | ..... | 17.00 | 12.68 | 14.67 | ..... | 14.77 |
| *M* | 1,450 | ..... | 16.65 | 16.91 | 15.89 | ..... | 15.52 | 16.02 | 14.60 | ..... | 15.74 | 16.09 | 15.49 | ..... | 11.28 | 12.27 | 11.67 |
| | 1,400 | 16.81 | 16.82 | 17.08 | 16.46 | 15.61 | 15.66 | 15.89 | 15.37 | 15.98 | 15.84 | 16.49 | 15.52 | 12.03 | 11.66 | 11.97 | 11.94 |
| | 1,350 | 17.50 | 16.48 | 16.82 | 16.72 | 16.20 | 15.45 | 15.99 | 15.47 | 16.51 | 15.71 | 16.01 | 15.67 | 12.08 | 12.13 | 11.52 | 11.71 |
| | 1,300 | 17.45 | ..... | 16.60 | 17.08 | 16.54 | 15.40 | 15.57 | 16.03 | 16.52 | 15.36 | 15.83 | 16.23 | 12.05 | 11.32 | 11.79 | 12.37 |
| | 1,250 | 17.54 | ..... | ..... | ..... | 16.79 | ..... | ..... | ..... | 16.69 | ..... | ..... | ..... | 12.07 | ..... | ..... | ..... |
| *N* | 1,450 | ..... | 16.29 | 17.27 | 17.63 | ..... | 15.12 | 16.19 | 16.97 | ..... | 15.95 | 16.36 | 17.37 | ..... | 12.77 | 12.92 | 13.83 |
| | 1,400 | 17.62 | 16.41 | 17.15 | 18.03 | 16.30 | 15.28 | 16.38 | 16.80 | 16.59 | 15.91 | 16.82 | 17.71 | 12.94 | 12.46 | 13.16 | 14.31 |
| | 1,350 | 17.64 | 16.46 | 17.81 | 18.74 | 16.70 | 15.52 | 17.11 | 17.55 | 17.30 | 15.91 | 17.09 | 17.87 | 13.29 | 12.48 | 13.01 | 14.03 |
| | 1,300 | 17.99 | 17.41 | 17.93 | 18.36 | 16.96 | 16.23 | 16.61 | 17.09 | 17.26 | 16.69 | 17.15 | 17.52 | 13.37 | 13.03 | 12.92 | 13.65 |

[1] The values presented in this table are averages of values for a group of 4 bars cast at the same pouring temperature.

In figure 6 these ratios are plotted for the transverse test bars of both plain carbon and alloy irons against moduli $E_1$. It may be seen that most $E_1/E_1(S)$ ratios of alloy irons approach very close to the value 1.060, whereas the same ratios applied to plain carbon irons give widely scattered values. It already has been mentioned that for the testing machine used in this and previous investigations, the initial portion (for loads less than 1,000 lb) of the load–total-deflection

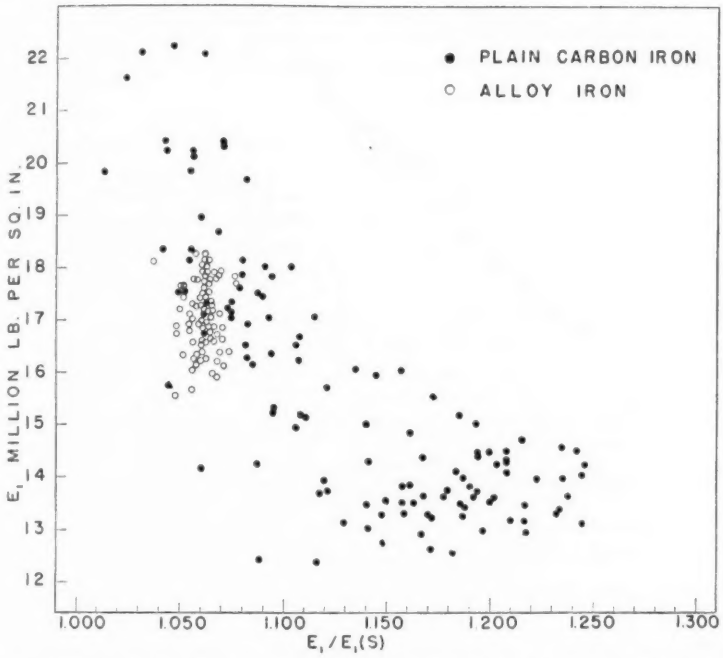


FIGURE 6.—*Relation of $E_1/E_1(S)$ and relative modulus of elasticity, $E_1$, for plain carbon and alloy cast irons.*

diagram cannot be regarded as accurate. On the other hand, the statement has been made that actually these initial portions of most diagrams appeared to be continuous smooth curves. In view of this fact it was thought that an approximate relationship can probably be obtained between the initial slope of these curves and the modulus $E$, if the tangent of angle $\alpha$, at which the initial portion of the load–total-deflection curve is inclined at its origin towards the deflection axis, is plotted[5] against modulus $E_1$. Thus, the angles, $\alpha$, of the continuous smooth curves obtained for the transverse test bars of plain carbon and alloy irons were measured by means of a protractor, and tangents of these angles were plotted against moduli $E_1$ (fig. 7).

The highest values of $E_1$ were obtained with iron *L* heated to a maximum temperature of 1,700° C, but in general (fig. 8), no definite relation was established between $E_1$ and the maximum heating tem-

[5] Method of plotting adopted after Carl Benedicks, *Om de fasta lösningarnas elasticitet*, Jernkontorets Ann. **124**, 225 (1940); also, *The elastic modulus of solid solutions*, Metallurgist, **20** (1941).

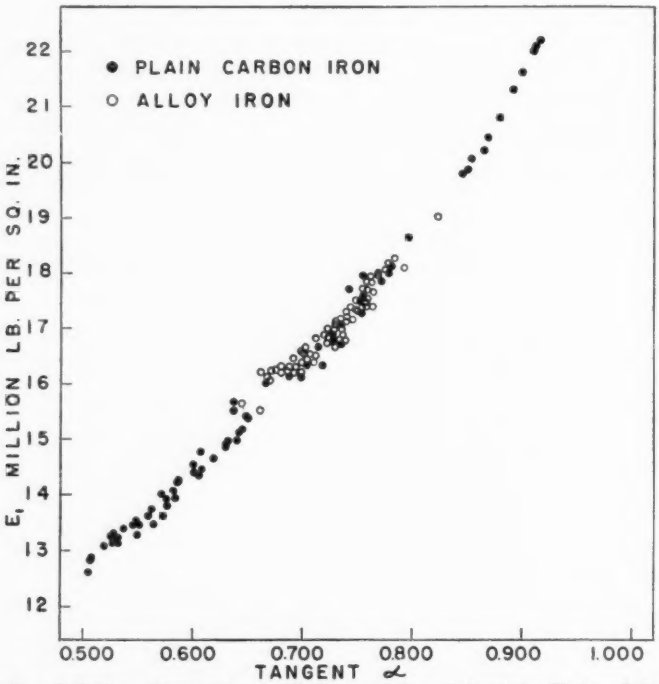


FIGURE 7.—*Relation of tangent $\alpha$ to relative modulus of elasticity $E_1$ for plain carbon and alloy cast irons.*

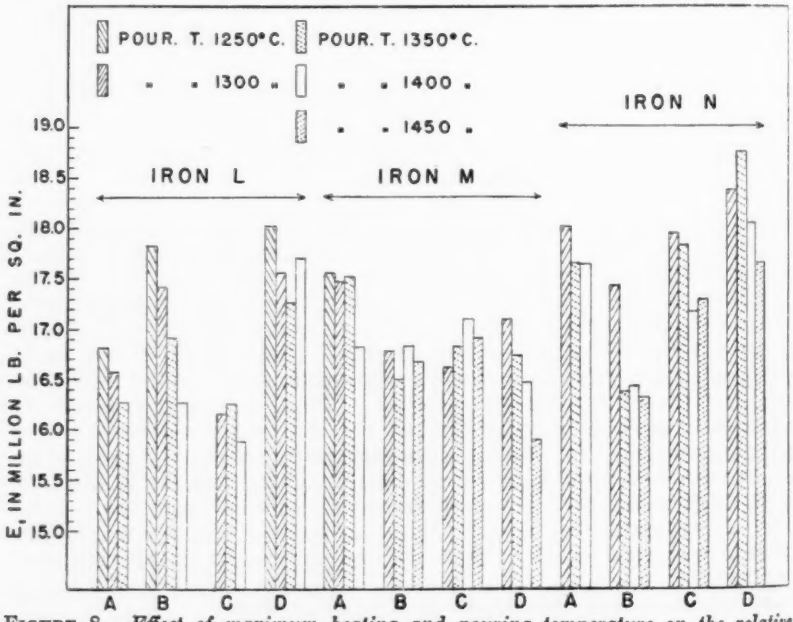


FIGURE 8.—*Effect of maximum heating and pouring temperature on the relative modulus of elasticity of irons L, M, and N.*

Maximum heating temperatures: *A*, 1,400° C; *B*, 1,500° C; *C*, 1,600° C; *D*, 1,700° C.

perature, whereas for the plain carbon irons there was a tendency for the values of $E_1$ to increase with increasing maximum heating temperature.

Effect of pouring temperature was practically the same for both alloy and plain carbon irons, that is, usually there was a decrease in $E_1$ values with increase in pouring temperatures. When comparing the moduli $E_1$ of alloy irons *L*, *M*, and *N* with those of plain carbon irons, it may be noted that moduli $E_1$ of alloy irons correspond to those of plain carbon iron *A*, heated to the maximum temperatures of 1,400°, 1,500°, and 1,600° C. However, the moduli of alloy irons are lower than moduli of iron *A* heated to maximum temperature of 1,700° C.

## 4. RESILIENCE

In agreement with common practice for cast iron, the term "resilience" is used in this paper to denote the work done in loading the specimen. The following resilience values are discussed below:

$W_1$=Ultimate total resilience obtained by measuring planimetrically the area below the load–total-deflection curve and between the origin and the ordinate drawn to the deflection curve at the point of rupture.

$W_2$=Ultimate triangular resilience, represented by a triangular area below a straight line drawn from the origin and the point of rupture on the load–total-deflection curve. It is obvious that triangular resilience only approximates the true resilience and that the degree of approximation decreases as the curvature of the load–total-deflection curve increases.

$W_3$=Ultimate elastic resilience was determined by calculating the triangular area below the ultimate elastic deflection curve on the assumption that this curve is a straight line. In view of the fact that ultimate elastic deflection curves deviate but slightly from a straight line, this assumption is permissible.

$W_4$=Ultimate plastic resilience. These resilience values were obtained by subtracting $W_3$ values from those of $W_1$.

The averages values of $W_1$ and $W_4$, as well as the ratios of $W_4/W_1$ expressed in percentage of $W_1$, for each group of bars cast at the same pouring temperature are shown in table 6. This table indicates that all these values are considerably lower for iron *L* than for irons *M* and *N*. The ultimate total-resilience values range as follows: for iron *L*, from 304 to 385 in.-lb; iron *M*, from 492 to 722 in.-lb; and iron *N*, 510 to 880 in.-lb. When drawing a comparison between alloy and plain carbon irons, it may be observed that plain carbon iron *A*, which showed total-resilience values from 220 to 375 in.-lb, approaches alloy iron *L*. Neither maximum heating nor pouring temperatures seem to have a considerable influence on these properties for irons *L* and *M*. However, a considerable improvement in these properties was observed for iron *N* when a lower range of pouring temperatures (1,300 to 1,350° C) was employed. When comparing all bars tested in this investigation, it may be noticed that iron *N* heated to the maximum temperature of 1,600° C and cast at pouring temperatures ranging from 1,300 to 1,350° C possessed the highest values of $W_1$ and $W_4$.

In connection with this observation it may be recalled that for plain carbon irons the effect of maximum heating and pouring temperatures was observed only for iron *A*, in which case there was a pronounced

TABLE 6.—*Resilience Values* [1]

| Maximum heat temperature °C | | 1,400 | | | 1,500 | | | 1,600 | | | 1,700 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Iron | Pouring temperature | Ultimate total resilience, $W_t$ | Ultimate plastic resilience, $W_p$ | Ratio $W_p/W_t$ | Ultimate total resilience, $W_t$ | Ultimate plastic resilience, $W_p$ | Ratio $W_p/W_t$ | Ultimate total resilience, $W_t$ | Ultimate plastic resilience, $W_p$ | Ratio $W_p/W_t$ | Ultimate total resilience, $W_t$ | Ultimate plastic resilience, $W_p$ | Ratio $W_p/W_t$ |
| | *° C* | *lb-in.* | *lb-in.* | *Percent* | *lb-in.* | *lb-in.* | *Percent* | *lb-in.* | *lb-in.* | *Percent* | *lb-in.* | *lb-in.* | *Percent* |
| *L* | 1,400 | | | | 341 | 73 | 21.41 | 311 | 56 | 18.00 | 335 | 70 | 20.90 |
| | 1,350 | 363 | 86 | 23.69 | | | | 332 | 61 | 18.37 | 304 | 52 | 17.11 |
| | 1,300 | 379 | 89 | 23.48 | 328 | 67 | 20.43 | 385 | 81 | 21.04 | 372 | 75 | 20.16 |
| | 1,250 | 319 | 81 | 25.39 | 305 | 60 | 19.67 | | | | 334 | 67 | 20.06 |
| *M* | 1,450 | | | | 706 | 265 | 37.54 | 533 | 174 | 32.65 | 492 | 161 | 32.72 |
| | 1,400 | 581 | 191 | 32.87 | 603 | 217 | 35.99 | 612 | 215 | 35.13 | 528 | 167 | 31.63 |
| | 1,350 | 640 | 230 | 35.94 | | | | 722 | 268 | 37.12 | 669 | 240 | 35.87 |
| | 1,300 | 659 | 242 | 36.72 | 692 | 253 | 36.56 | 557 | 190 | 34.11 | 592 | 198 | 33.45 |
| | 1,250 | 637 | 232 | 36.42 | | | | | | | | | |
| *N* | 1,450 | | | | 510 | 131 | 25.69 | 644 | 189 | 29.35 | 581 | 153 | 26.33 |
| | 1,400 | 617 | 186 | 30.15 | 568 | 153 | 26.94 | 665 | 189 | 28.42 | 533 | 134 | 25.14 |
| | 1,350 | 619 | 189 | 30.53 | 608 | 168 | 27.63 | 880 | 277 | 31.48 | 751 | 205 | 27.30 |
| | 1,300 | 658 | 204 | 31.00 | 661 | 194 | 29.35 | 799 | 250 | 31.29 | 672 | 198 | 29.46 |

[1] Average values for each group of bars cast at the same pouring temperature.

decrease in resilience with increasing pouring temperatures. An increase in resilience with increasing maximum heating temperature was particularly evident in the bars of that iron poured at 1,350° C.

According to data compiled by Tucker [4], neither the breaking load, deflection, nor resilience values gave reliable indications of the resistance to thermal shock, but the plastic resilience, expressed in percentage of the total resilience, furnished a measure of the relative toughness of his irons. From this viewpoint, irons *M* and *N* should be more resistant to thermal shock than iron *L*. None of these irons, however, is superior, in this respect, to the plain carbon irons, previously examined. Actually all of them are inferior to a medium cylinder iron, *B*, whose plastic to total-resilience ratios ranged from 42 to 49 percent.

It is well known that silicon has a great effect on the physical properties of cast iron in general. In his work on the influence of phosphorus on iron, MacKenzie [5] plotted the ultimate total-deflec-

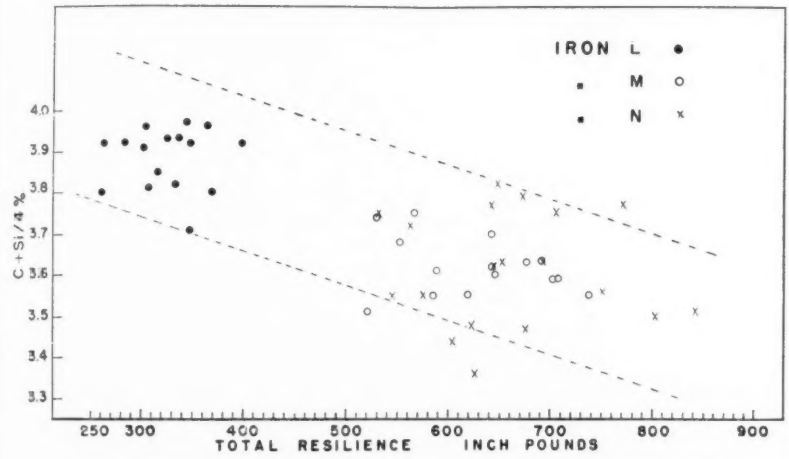


FIGURE 9.—*Relation of total resilience to carbon and silicon contents.*

tion values against the carbon content plus one-fourth of the silicon content and found that there was an increase of deflection with an increase of C+Si/4 values. His diagram indicated that deflection depends more on C+Si/4 values than on phosphorus content [6]. An attempt was made by the present writers in their previous paper [1] to find whether a corresponding relation to C+Si/4 content may be shown for the ultimate total-resilience values. Although a probable trend of the plotted points was outlined, it was found that the results obtained did not warrant any definite conclusion. In the present investigation, the values C+Si/4 for irons *L*, *M*, and *N* were plotted against $W_1$, $W_3$, and $W_4$. Although the plotted points are widely scattered, nevertheless, as may be seen in fig. 9, there is a definite trend for the ultimate total resilience to increase with a decrease of C+Si/4 values. A similar relation has been found for the ultimate plastic and elastic resiliences. Another interesting relation for the resilience values has been demonstrated by MacKenzie [7] for 1.2- by

18-in. bars tested transversely. The ratios of true resilience to triangular resilience were compared with ratios of modulus of elasticity at one-half load to ultimate modulus of elasticity. He showed that these ratios, when plotted in a logarithmic scale, were almost directly proportional to each other. It should be noted that in MacKenzie's experiments both modulus of elasticity at one-half load and ultimate modulus of elasticity were "secant moduli."

In the present investigation, the ratios $E_1(S)/E_2(S)$ were plotted (fig. 10) against ratios $W_1/W_2$ on linear scale; this gives roughly the

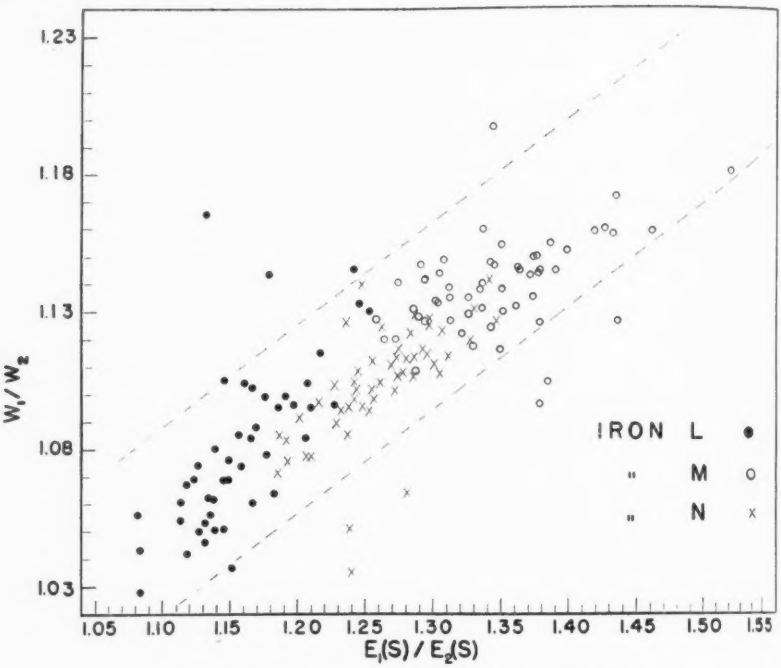


FIGURE 10.—*Relation of $E_1(S)/E_2(S)$ to $W_1/W_2$.*

same distribution of the points as a logarithmic plot, since the coordinates of the points are not far different from unity. Since $E_2$ is nearly equal to $E_1(S)$ (fig. 5), nearly the same relation was obtained for the ratios $E_1(S)/E_2(S)$ and $E_2/E_2(S)$. Both $E_1(S)/E_2(S)$ (fig. 10) and $E_2/E_2(S)$ tended to increase with increasing values of $W_1/W_2$.

## 5. HARDNESS

Brinell hardness numbers were determined on disks three-fourths inch thick cut from the tested transverse bars adjacent to the fracture. Three impressions were made on each disk; one near the center and two at points midway between the center and periphery. Two diameters were measured for each indentation, and the average of these six readings was used as the hardness number of a given specimen.

The Brinell numbers for the irons examined were as follows:

Iron *L*, 217 to 255.
Iron *M*, 255 to 269.
Iron *N*, 302 to 341.

No consistent relation was observed between the Brinell number and the transverse strength, maximum heating or pouring temperatures.

## VI. MICROSCOPIC EXAMINATION

After the hardness was determined on one side of a disk, the opposite side (adjacent to the fracture) was ground, lapped on a lead-tin plate charged with fine emery, further lapped on a second plate charged with finer emery, and finally polished with an aqueous suspension of rouge, in an automatic polishing machine. Before final etching, the specimens were subjected to alternate polishing and etching operations. All the specimens were examined microscopically as polished and as etched with 1-percent solution of nitric acid in ethyl alcohol. The micrographs described below represent typical structures of the irons.

Figure 11 indicates that of two transverse bars of iron *L* the bar possessing greater strength and hardness shows somewhat less ferrite, finer graphite, and more pronounced dendrites. The total and combined carbon contents for the stronger bars were 3.24 and 0.60 percent, respectively, and for the companion bar 3.34 and 0.56 percent. Molybdenum and nickel contents were around 0.75 and 1.05 percent, respectively. The austenite-pearlite transformation has not been suppressed. Both bars were poured at low temperatures. It is evident, therefore, that the difference observed in this case is an effect of the maximum heating temperature.

Figure 12 represents iron *M*. Here again, the finer graphite and more pronounced dendritic structures were associated with greater transverse strength. When etched and examined at lower magnification, this specimen exhibits long dendrites extending in a radial direction almost to the center of the specimen, the dendrites of the companion specimen being much shorter and fewer in number. The matrix of these specimens consists of coarse pearlite and the so-called "acicular structure" with islands of fine pearlite. It has been shown by various investigators [8, 9, 10] that an addition of molybdenum to cast iron reduces the rate of transformation of austenite and causes the appearance of a peculiar "acicular" structure. This structure has been called acicular pearlite, acicular troostite, or acicular ferrite. It may be also called "pseudomartensite." In subsequent discussion, this structure for convenience will be designated as "acicular" structure. Two inclusions (fig. 12, *D*), presumably "magnanese sulfide," apparently served as nuclei of the graphite formations within fine pearlitic areas.

In spite of a rather small difference between the mechanical properties of these two transverse test bars of iron *N*, a considerable difference was observed in their structures. Finer graphite globules and flakes are associated with a somewhat stronger bar (fig. 13, *C* and *D*). It may also be observed that the higher Brinell number and relative modulus of elasticity were obtained with the bar possessing larger graphite nodules. Both specimens exhibited dendritic structures. The grayish-white areas (fig. 13, *D*), representing the midribs and branches of the dendrites, appear at higher magnification (fig. 14, *C*) as austenite at the initial stage of its transformation. A spot showing laminar graphite surrounding small crystals of manganese sulfide (fig. 13, *D*) is of interest.

A large portion of the free carbon of the lower strength transverse test bar (fig. 13, *A* and *B;* fig. 14 *A* and *B*) is present in the form of globules, consisting of aggregates of small graphite flakes. In the middle of some of these globules the bluish-gray inclusions, presumably manganese sulfide, are plainly seen. A patch of eutecticlike graphite resembling the Widmanstätten structure and associated with globular and coarse flaky graphite is visible in figure 13 (*B*) and figure 14 (*A*).

Other interesting structural features are the graphite eutectic situated within a graphite globule in figure 14 (*B*) and the "fluffy" appearance of the edges of some graphite flakes shown in figures 13 (*B*) and 14 (*A*). The secondary graphite, that is, hypereutectoid and eutectoid graphite, is generally deposited on existing graphite flakes in the form of a smooth band which is similarly oriented to the main body and is therefore difficult to show. Sometimes, however, the secondary graphite is deposited on the graphite lamellae in an irregular manner, so that the edges have a "fluffy" appearance [11, 12].

With regard to Widmanstätten structures, Morrogh [11] believes that the grain size of the original austenite does not determine whether the graphite will be deposited normally or in Widmanstätten form, and the conditions favorable for the development of the graphite Widmanstätten pattern are a controlled rate of cooling, neither extremely slow nor extremely fast, and a eutectic graphite structure consisting of a few very coarse flakes. The actual rate of cooling required to produce this structure must be very critical, as the graphite Widmanstätten pattern is seen in a fully developed form only very rarely.

The chemical analysis and Brinell hardness of two test bars represented in figure 15 (*A*, *B*, *C*, and *D*) are practically the same, but their transverse strengths differ. The characteristic structural features of the higher strength bar (fig. 15, *C* and *D*) are globular and flaky graphite, well-developed dendritic pattern, free carbide, and a fine acicular structure. The lower strength bar of the same heat (fig. 15, *A* and *B*) contained globular and whorl-like formations of graphite, coarse acicular structure, and a small amount of fine pearlite. The dendritic pattern of this bar was less pronounced than that of the companion bar.

An interesting feature of the structure presented in figure 15 (*B*) is the inclusion of a perfect hexagonal form with the light twinning-like band in the middle. It appears that this inclusion has been moved during solidification from its original seat and slightly rotated. It has the appearance of a cube resting on one of its edges. Somewhat similar inclusions but without the light band in the middle were shown by Allen [13] and Ellis [14]. Both of these authors described it as a manganese sulfide crystal. Ellis, however, remarks that manganese sulfide crystals may not be pure manganese sulfide, but rather mixtures of sulfides.

It is known that manganese sulfide inclusions possess a cubic crystal structure and appear in cast iron as dove-gray colored crystals of square, triangular, trapezoidal, etc., form. In steel they are generally present as dove-gray colored globules. On the other hand, iron sulfide has a hexagonal crystal structure and is lighter [15] in color than manganese sulfide.

Whiteley [16] was able to show that at temperatures above the solidus the sulfide in steel consisted predominantly of iron sulfide.

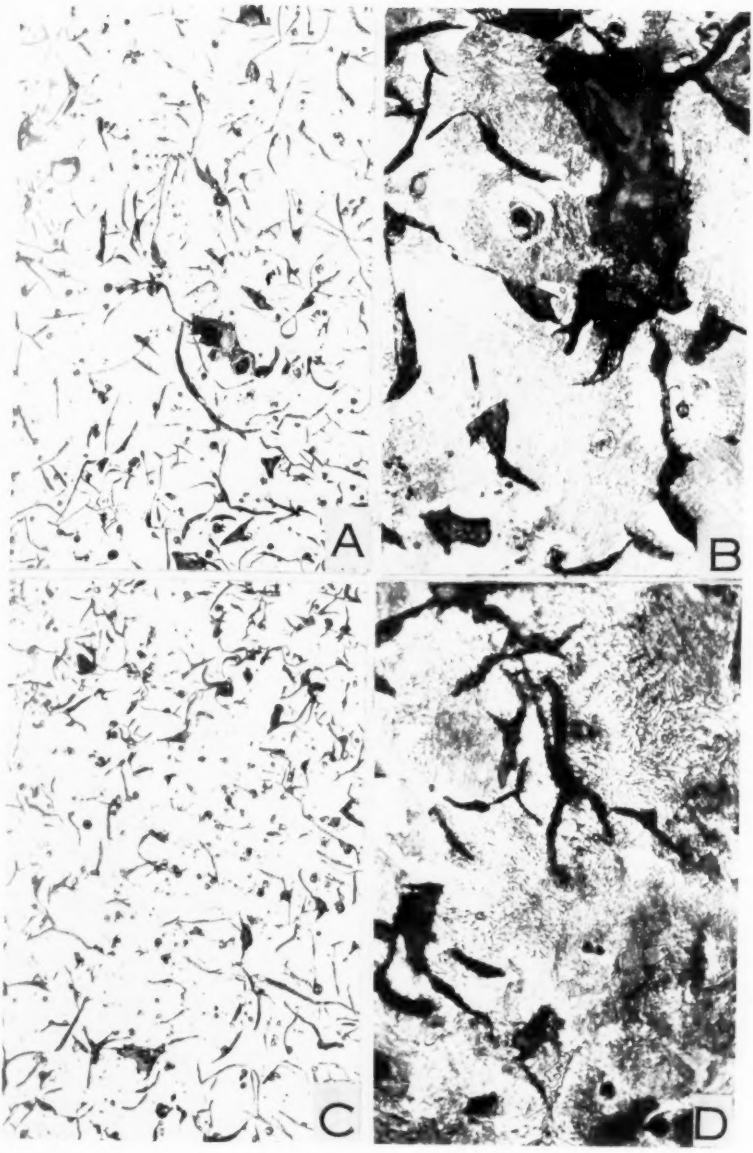


FIGURE 11.—*Iron L.*

Maximum temperature for *A* and *B*, 1,500° C; *C* and *D*, 1,700° C. Pouring temperature for *A* and *B*, 1,400° C; *C* and *D*, 1,300° C. Modulus of rupture for *A* and *B*, 61,000 lb/in.²; *C* and *D*, 76,000 lb/in.² $E_t = 16\times10^6$ lb/in.² for *A* and *B*. $E_t = 17.7\times10^6$ lb/in.² for *C* and *D*. Brinell hardness numbers for *A* and *B*, 229; *C* and *D*, 241. *A* and *C*, unetched, ×100; *B* and *D*, etched, ×500.

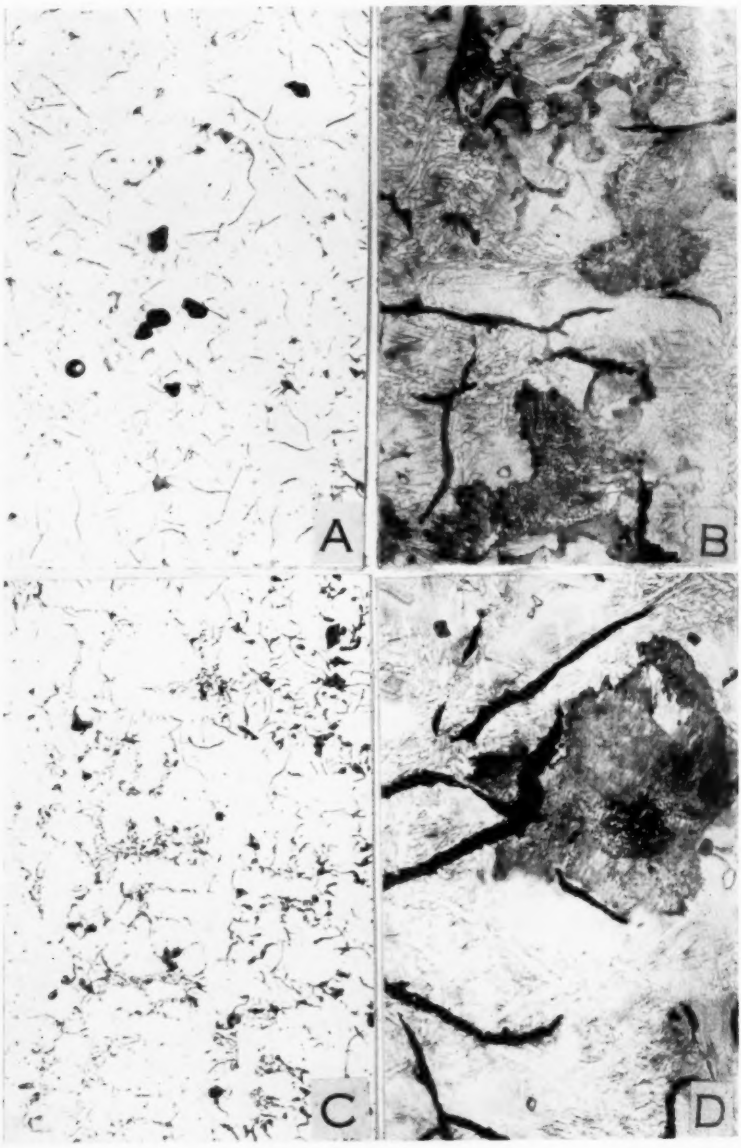


FIGURE 12.—*Iron M.*

Maximum temperature for *A* and *B*, 1,500° C; *C* and *D*, 1,600° C. Pouring temperature for *A*, *B*, *C* and *D*, 1,350° C. Modulus of rupture for *A* and *B*, 78,000 lb/in.$^2$; *C* and *D*, 93,000 lb/in.$^2$. $E_t = 16.1 \times 10^6$ lb/in.$^2$ for *A* and *B*. $E_t = 17.0 \times 10^6$ lb/in.$^2$ for *C* and *D*. Brinell hardness number for *A*, *B*, *C*, and *D*, 255. *A* and *C*, unetched, ×100; *B* and *D*, etched, ×500.

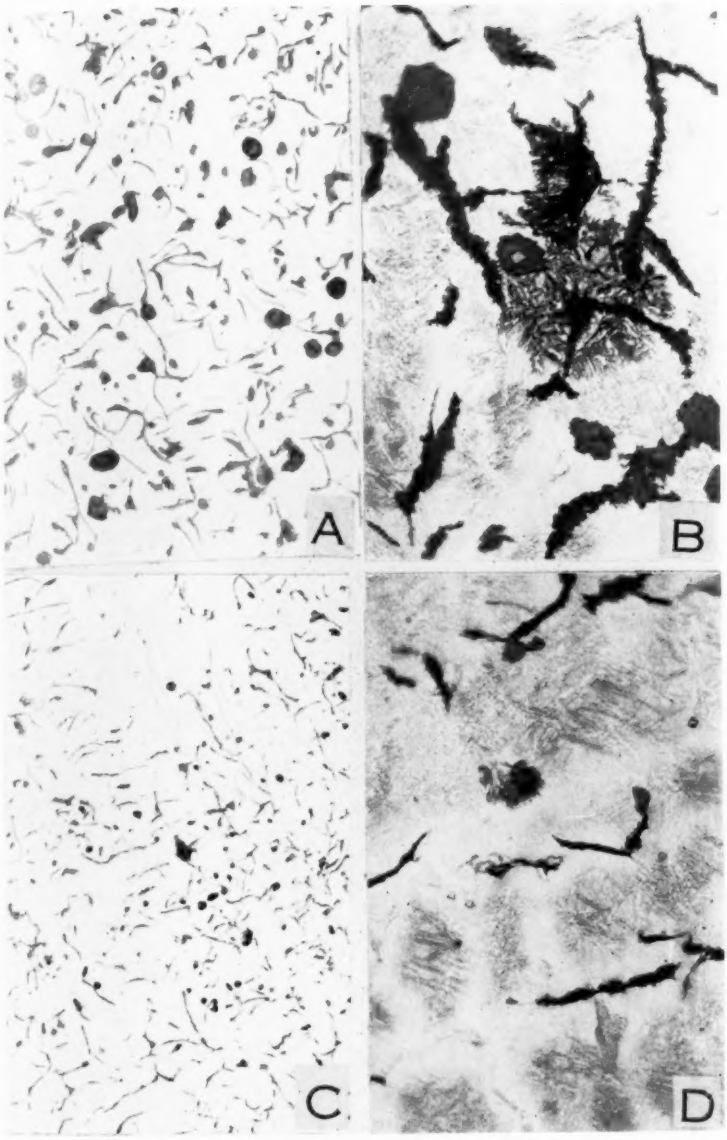


FIGURE 13.—*Iron N.*

Maximum temperature, 1,400° C. Pouring temperature for *A* and *B*, 1,400° C; *C* and *D*, 1,350° C. Modulus of rupture for *A* and *B*, 86,400 lb/in.$^2$; *C* and *D*, 99,300 lb/in.$^2$. $E_t = 17.9 \times 10^6$ lb/in.$^2$ for *A* and *B*. $E_t = 17.6 \times 10^6$ lb/in.$^2$ for *C* and *D*. Brinell hardness numbers for *A* and *B*, 311; *C* and *D*, 302. *A* and *C*, unetched, ×100; *B* and *D*, etched, ×500.

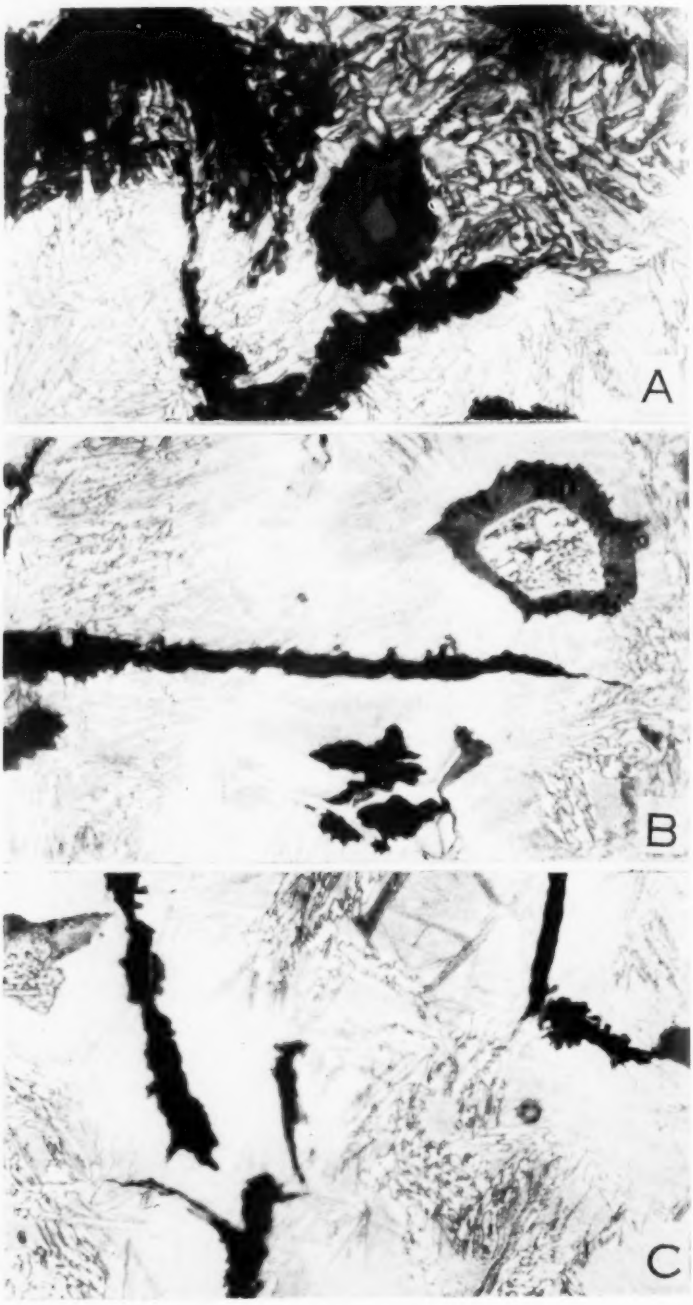


FIGURE 14.—*Iron N.*

*A* and *B* represent specimen shown in figure 13 (*A* and *B*), *C* represents specimen shown in figure 13 (*C* and *D*). Etched, ×1,500.

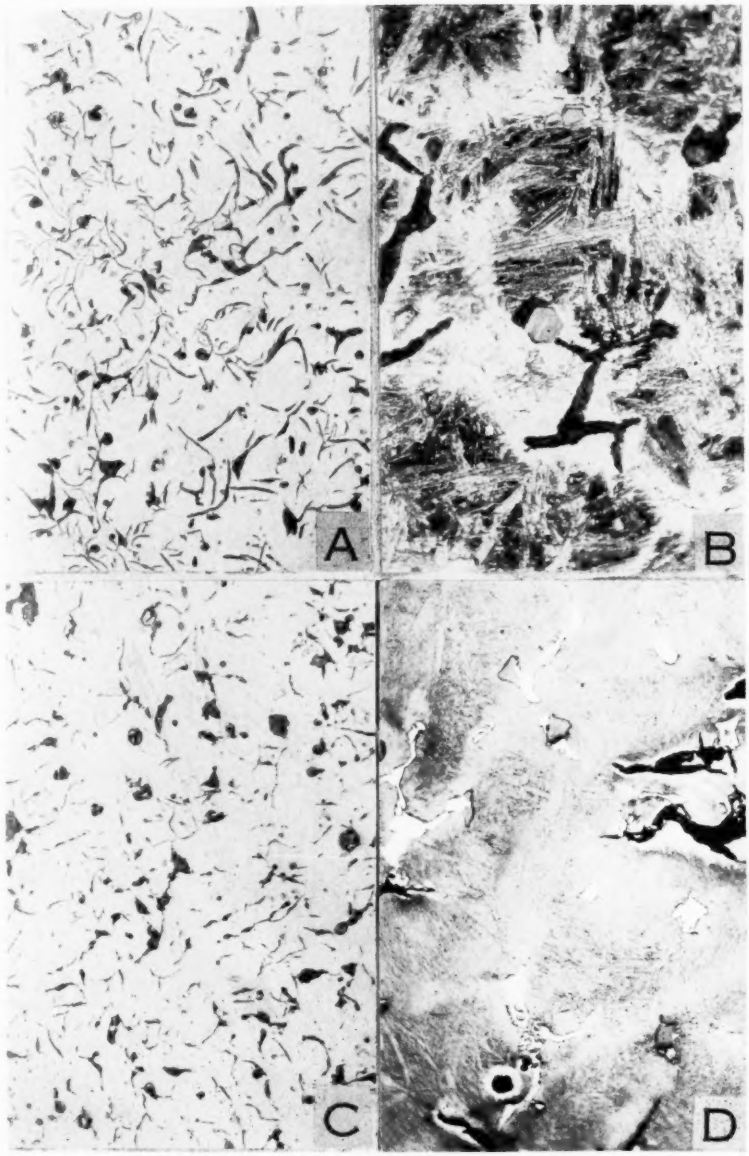


FIGURE 15.—*Iron N.*

Maximum temperature, 1,600° C. Pouring temperature for *A* and *B*, 1,450° C; *C* and *D*, 1,350° C. Modulus of rupture for *A* and *B*, 89,000 lb/in.$^2$; for *C* and *D*, 112,100 lb/in.$^2$ $E_t = 17.3 \times 10^6$ lb/in.$^2$ for *A* and *B*. $E_t = 18.7 \times 10^6$ lb/in.$^2$ for *C* and *D*. Brinell hardness number for *A*, *B*, *C*, and *D*, 311. *A* and *C*, unetched, ×100; *B* and *D*, etched, ×500.

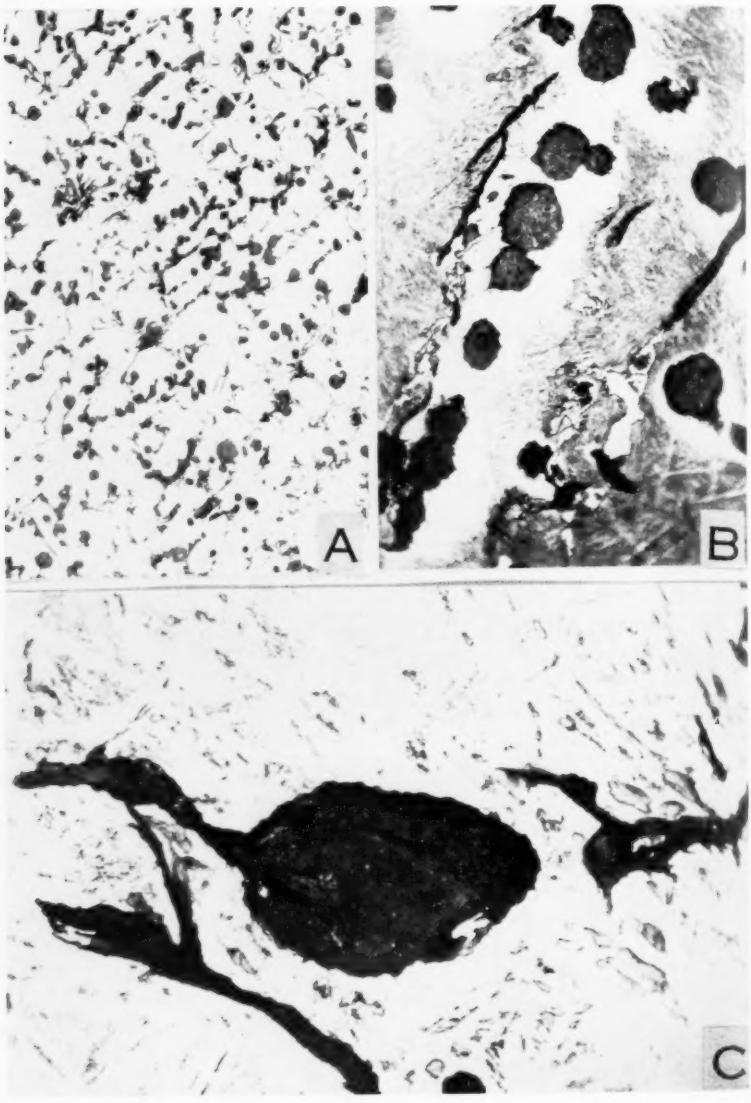


FIGURE 16.—*Iron N.*

Maximum temperature, 1,700° C. Pouring temperature, 1,350° C. Modulus of rupture, 104,000 lb/in.$^2$ $E_t$=18.60×10.$^6$lb/in$^2$. Brinell hardness number 341. *A*, unetched, ×100; *B*, etched, ×500; *C*, etched, ×1,500.

The appearance of iron sulfide at these temperatures is due to the fact that the reaction $FeS+Mn \rightleftharpoons MnS+Fe$ will tend to proceed toward the left at higher temperatures. At very drastic quenching from the liquid state, this investigator was able to show that FeS was present in liquid steel containing 0.06 percent of S and 0.6 percent of Mn. Iron sulfide may dissolve in the manganese sulfide.

Consideration of all of this evidence suggests that the inclusion shown in figure 15 (*B*) is probably a mixture of manganese and iron sulfides and that the light band in the middle is the remnant of iron sulfide proper.

In the middle portion of the flake, below the hexagonal inclusion just described (fig. 15, *B*), three dark lines crossing the flake at angles of about 60 degrees to its longitudinal axis may be noticed. These lines resemble the needles described by Hanemann and Schrader [17] and also by Morrogh [11]. They have shown that secondary graphite sometimes forms small needlelike crystals of different orientation from the graphite flake. If the flake is in its dark position, then the needles appear bright; and if the flake is in its bright position, the needles appear dark.

Figure 16 shows the structure of iron *N* heated to 1,700° *C* and poured at 1,350°C. The modulus of elasticity and Brinell hardness of this bar are about the highest obtained in the present investigation. It seems that most of the free carbon is present here in the form of globules (fig. 16, *A*). A row of graphite globules is shown in figure 16 (*B*). They have a spongy-like appearance, some of them being associated with graphite flakes, as may be seen in figure 16 (*C*). It appears as if they originated from the nucleus situated at the right end of the flake inside of the graphite nodule, but it is difficult to determine which of them, flake or globule, was formed first. If this globular graphite is of a temper-carbon nature, then the graphite flakes are eutectic graphite and the nodules are formed after solidification of the metal. Although the nodular formation of graphite is probably best developed in castings made from metal heated to 1,700° C, it cannot be stated that the high maximum heating temperature is responsible for such structure, because some nodular graphite was observed for the same iron, *N*, which had been heated only to 1,400° C and poured at 1,350° C (figs. 13, *A* and *B*). This structure is evidently characteristic for iron *N*, and seems to be a contributing factor in obtaining the higher values of the relative modulus of elasticity and Brinell hardness.

The structure of the matrix of the specimen in figure 16 (*B*) is acicular. The white area surrounding the graphite nodules when resolved at higher magnification (×1500) is shown in figure 16 (*C*). This structure resembles somewhat the micrographs presented by Davenport, Grange, and Hafsten [18] showing the initial and second stages of transformation of coarse-grained austenite at 540°C.

Microscopic examination indicates that a pearlitic matrix with the presence of some ferrite is responsible for the low strength of iron *L* as compared with irons *M* and *N*. The relatively low strength and Brinell hardness of iron *M* as compared with iron *N* may be caused by some pearlite in its structure. Acicular structure and fine graphite are associated with high strength in the irons examined. Iron *N* possessed large graphite globules and fine acicular matrix and had the highest Brinell number. In general, the globular formation of graphite seems to be a contributing factor in obtaining high values of relative modulus of elasticity and Brinell hardness.

It was found, when examining test bars of the same heat, that the bars possessing greater strength showed a pronounced dendritic pattern. Since it is commonly accepted that random distribution of graphite particles produces stronger cast iron than does dendritic structure, it may be inferred that the high strength bars showing dendritic patterns would possess still greater strength if their graphite particles were arranged at random.

## VII. SUMMARY

1. The mechanical properties of three alloy irons (*L*, a nickel-molybdenum iron; *M* a nickel-molybdenum-chromium, low-manganese, medium-silicon iron; and *N*, a nickel-molybdenum-chromium, high-manganese, high-silicon iron) were determined by measurements under transverse loading.

2. The average transverse strength, ultimate total and elastic deflections, resilience, and Brinell hardness of irons *M* and *N* were found to be superior to those of iron *L*.

3. The maximum heating temperature showed no effect on the transverse strength of irons *L* and *M*, but the moduli of rupture of iron *N* were somewhat higher for the maximum heating temperatures of 1,600° and 1,700° C than for 1,400° and 1,500° C. The highest moduli of elasticity of all the bars tested were obtained with iron *N* at the heating temperature at 1,700° C, but in general no definite relation could be established between the relative moduli of elasticity and the maximum heating temperature. The lower pouring temperatures, ranging from 100° to 150° C above the liquidus, tended to increase the strength and relative modulus of elasticity of the irons examined. Neither maximum heating nor pouring temperatures exerted much influence on the resilience values for irons *L* and *M*, but a considerable improvement in these properties was observed for iron *N* when a lower pouring temperature was employed.

4. The elastic-deflection curves of the alloy irons studied in this investigation were similar to those of the plain carbon irons described in the previous paper, that is, they were straight lines in their lower portion, but beginning at a certain point (approximately three-fifths of the breaking load), they inclined toward the deflection axis.

5. Four relative moduli of elasticity were determined: $E_1$, calculated from the lower portion of the elastic-deflection curve; $E_1(S)$, secant modulus corresponding to the load at which $E_1$ was calculated; $E_2$, ultimate modulus computed from the elastic-deflection curve at the breaking point; and $E_2(S)$, ultimate secant modulus at the breaking load. The values of these moduli decreased in the following order: $E_1$, $E_2$, $E_1(S)$ and $E_2(S)$. There was a rather small difference between $E_1$, $E_2$, and $E_1(S)$ values, but $E_2(S)$ was considerably lower.

6. The ratios of the average ultimate plastic resilience, $W_4$ (the area below the load–plastic-deflection curve between the origin and the ordinate drawn to the plastic-deflection curve at the point of rupture), and ultimate total resilience, $W_1$ (area below the load–total-deflection curve and between the origin and the ordinate drawn to the total deflection curve at the point of rupture), were considerably higher for irons *M* and *N* than for iron *L*.

7. There is a definite trend for the ratios $E_1(S)/E_2(S)$ and $E_2/E_2(S)$ to increase with an increase of ratio $W_1/W_2$, where $W_1$ is the ultimate

total resilience and $W_2$ the ultimate triangular resilience, represented by a triangular area below a straight line drawn from the origin to the point of rupture on the load–total-deflection curve.

8. Comparison of alloy irons *L*, *M*, and *N* with plain carbon irons *A*, *B*, and *C* previously investigated indicates that:

(a) Iron *A*, showing higher strength, elasticity, and resilience values than companion plain carbon irons, possesses strength and resilience equivalent to those of a nickel-molybdenum iron.

(b) The relative moduli of elasticity of iron *A* heated to the maximum temperature of 1,700° C are higher than those of alloy irons.

(c) The beneficial effect of the maximum heating temperature on the moduli of rupture and elasticity was more pronounced for the plain carbon irons than for alloy irons. The effect of pouring temperature for both plain carbon and alloy irons, was about the same, that is, these properties showed a tendency to increase with a decrease in pouring temperature.

(d) The plastic to total resiliences ratios of plain carbon iron *B* (a medium cylinder iron) are higher than those of alloy irons.

(e) If the proportion of plastic deflection to the total deflection at fracture is accepted as an index of plasticity of cast iron, an alloy iron, *L*, may be considered as being the most rigid and plain carbon iron *B* the least rigid.

9. The structure of iron *L* consists of flaky graphite and pearlite. The matrix of irons *M* and *N* appears to be made up of the transition product of austenite, an "acicular" structure.

10. The graphite of iron *N* shows a tendency to form globules. This was particularly pronounced in the specimen of this iron when heated to the maximum temperature of 1,700° C and poured at 1,350° C. It is probable that the nodular graphite structure is a contributing factor in obtaining the higher values of the relative modulus of elasticity and Brinell hardness. Some unusual structures of iron *N* were observed, and a tentative explanation was offered for the following: a patch of a eutecticlike graphite resembling the Widmanstätten pattern; the fluffy appearance of the edges of some graphite flakes; an inclusion, presumably manganese sulfide, of a perfect hexagonal form with the light twinninglike band in the middle; and the dark lines observed on a graphite flake and crossing it at about a 60-degree angle.

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# APPLICATION OF THE DROPPING-MERCURY ELECTRODE TO THE INVESTIGATION OF THE POLYHYDROXY ACIDS AND LACTONES

By Harry Matheson, Horace S. Isbell and Edgar Reynolds Smith

**ABSTRACT**

The polarographic method is used in a study of the polyhydroxymonocarboxylic acids, their lactones, lactides, and other condensation products. With a tetraethylammonium chloride environment, polarographic waves are obtained which show the behavior of the hydroxy acids and their lactones with respect to electrolytic reduction and the products which they form in dilute aqueous solution.

Freshly prepared solutions of the aldonic acids give the ordinary hydrogen wave but do not give waves which correspond to the reduction of the carboxyl group. When a solution containing an aldonic acid is allowed to stand, the wave due to the hydrogen ion decreases and a wave caused by the gamma lactone appears. In the presence of oxygen a wave, apparently caused by some substance produced by the interaction of the sugar acid, mercury, and oxygen, forms at about $-1.1$ v. The formation of this wave is accompanied by a corresponding decrease in the hydrogen wave. Freshly prepared solutions of the delta lactones of the aldonic acids give waves at about $-2.3$ v, with respect to a mercury anode, which appear to be due to the reduction of the lactones. The heights of these waves decrease with time until, after several hours, they disappear. The absence of an appreciable delta lactone wave in a 0.01 *M* aqueous solution of an aldonic acid shows that the position of the equilibrium between the free acid and the delta lactone is far toward the free acid. The gamma lactones of the aldonic acids give polarographic waves at potentials slightly higher than the delta lactones. When a solution containing a gamma lactone is allowed to stand, the height of the gamma lactone wave decreases while a wave corresponding to the reduction of the hydrogen ion appears. The inflection points for the gamma lactone waves vary only slightly with the configuration of the groups comprising the lactone structure. This small variation in the inflection points shows a regularity which indicates that the stereomeric positions of the hydroxyl groups are of importance. When the hydroxyl of carbon 2 and the residual carbon group attached to carbon 4 are in the *cis* position, the reduction potential seems to be higher than it is when these groups are in the *trans* position.

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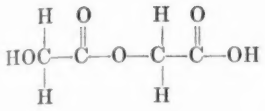
## I. INTRODUCTION

The hydroxy acids, of which lactic acid and gluconic acid are important examples, combine within themselves the properties of a carboxylic acid and of an alcohol, and consequently are capable of forming derivatives both as acids and as alcohols. All hydroxy acids lose water under certain conditions to yield esterlike compounds, of which the lactides and lactones are typical examples. When the hydroxy acid is dissolved in water, the esterification reactions may occur spontaneously to establish an equilibrium between the free acid and various condensation products. The condensation may take place between the carboxyl of one molecule and a hydroxyl of another, or it may take place intramolecularly. Thus, two molecules of glycolic acid combine with the loss of one molecule of water to give diglycolic acid (I), or with loss of two molecules of water to form glycolide (II); lactic acid forms an analog of diglycolic acid and also the lactide (III); erythronic acid forms the gamma lactone (IV); gluconic acid forms a gamma lactone (V), a delta lactone (VI), and a condensation product of unknown structure. The lactides and lactones can be isolated under suitable conditions and their presence in relatively concentrated solutions can be readily shown, but heretofore no suitable method has been available for investigating the composition of very dilute solutions of such compounds.



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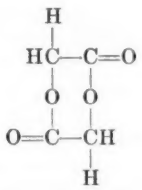
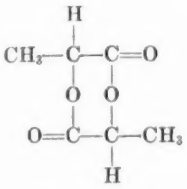
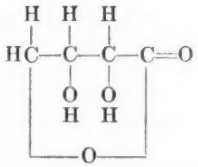


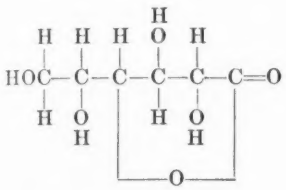
II. Glycolide



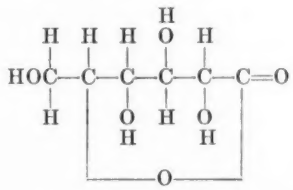
III. Lactide



IV. *d*-Erythrono-γ-lactone



V. *d*-Glucono-γ-lactone



VI. *d*-Glucono-δ-lactone

The polarographic method for the determination of "reduction potentials" [1] by means of the dropping-mercury electrode is particularly useful for the detection of reducible substances. Prior investigations have established that the esters, lactones, and anhydrides of carboxylic acids can be reduced chemically, whereas the free acids are extremely resistant to reduction. The reduction of the lactones of the aldonic acids is a reaction of importance, as it serves as a means of passing from the acid to the corresponding aldose, which may then be reduced to the alcohol. Although in polarographic investigations the conditions differ considerably from those commonly used in chemical reductions, it seemed probable that use of the polarographic method would give "reduction potentials" and would provide a means for studying the equilibrium between the hydroxy acids and their condensation products.

## II. OUTLINE OF EXPERIMENTAL METHOD AND RESULTS

The experimental approach to the problem, in its broader aspects, was somewhat empirical. Solutions of the pure acids, lactones, and lactides in several simple environmental solutions were prepared, and

[1] These "reduction potentials" are not, in all cases, the "redox" potential of an oxidant-reductant pair.

polarograms were made from time to time. The polarograms often showed typical reduction waves, which occurred at characteristic potentials and varied in height as the composition of the solutions changed with either the formation or the cleavage of the esterlike compounds.

To determine experimental conditions which bring out the characteristic waves for the substances under investigation, measurements were made in several environmental solutions. Müller [1] [2] has shown the desirability of using buffered environmental solutions in organic polarographic work, and in our early measurements attempts were made to use solutions buffered with lithium phosphate (0.05 *M*, pH 6.4) and lithium tetraborate (0.05 *M*, pH 9.1); but on account of the neutralizing action of the buffer and the reduction of the lithium ion, the solutions did not give waves characteristic of the acids or the lactones. Measurements with unbuffered solutions containing lithium chloride revealed waves which appeared to be characteristic of the gamma and delta lactones; but for many of the aldonic acids these waves occurred at potentials near the decomposition potential of lithium chloride, and consequently the measurements were not satisfactory. Thus, it was necessary to use a supporting electrolyte which has a very high decomposition potential, and tetraethylammonium chloride was selected for this purpose.

In agreement with their chemical properties, the freshly dissolved aldonic acids give a large wave at the potential corresponding to the reduction of hydrogen ion but fail to give any other waves. The freshly dissolved delta and gamma lactones do not give the hydrogen wave but give waves presumably caused by the reduction of the lactone to the corresponding sugar, at potentials which range from −2.2 to −2.7 v. With the exception of the wave for *d*-glucono-$\gamma$-lactone, which occurred at −2.2 v, the waves for the 17 gamma lactones studied occurred at potentials ranging from −2.4 to −2.7 v. In some cases there appear to be two waves which suggest a stepwise reduction, or the progressive reduction of the lactone (see the curve for lactobiono-$\delta$-lactone, fig. 2). The delta lactones of *d*-gluconic, *d*-mannonic, and *l*-rhamnonic acids appear to be reduced at slightly lower potentials than the corresponding gamma lactones. It is of interest to note also that the delta lactone of lactobionic acid is reduced at approximately the same potential as the delta lactone of *d*-gluconic acid. Thus, a galactosido group attached to carbon 4 of *d*-glucono-$\delta$-lactone does not materially alter the reduction potential. Compounds of the lactide type seem to give a wave at about −2.2 v. The polarograms given in figures 1 and 2 illustrate the character of the curves obtained for free acids, lactones, and lactide. The changes in the polarograms which were found to take place when the solutions were allowed to stand are discussed in section IV, and a more detailed description of the apparatus and the procedure is given in the next section.

[2] Figures in brackets indicate the literature references at the end of this paper.

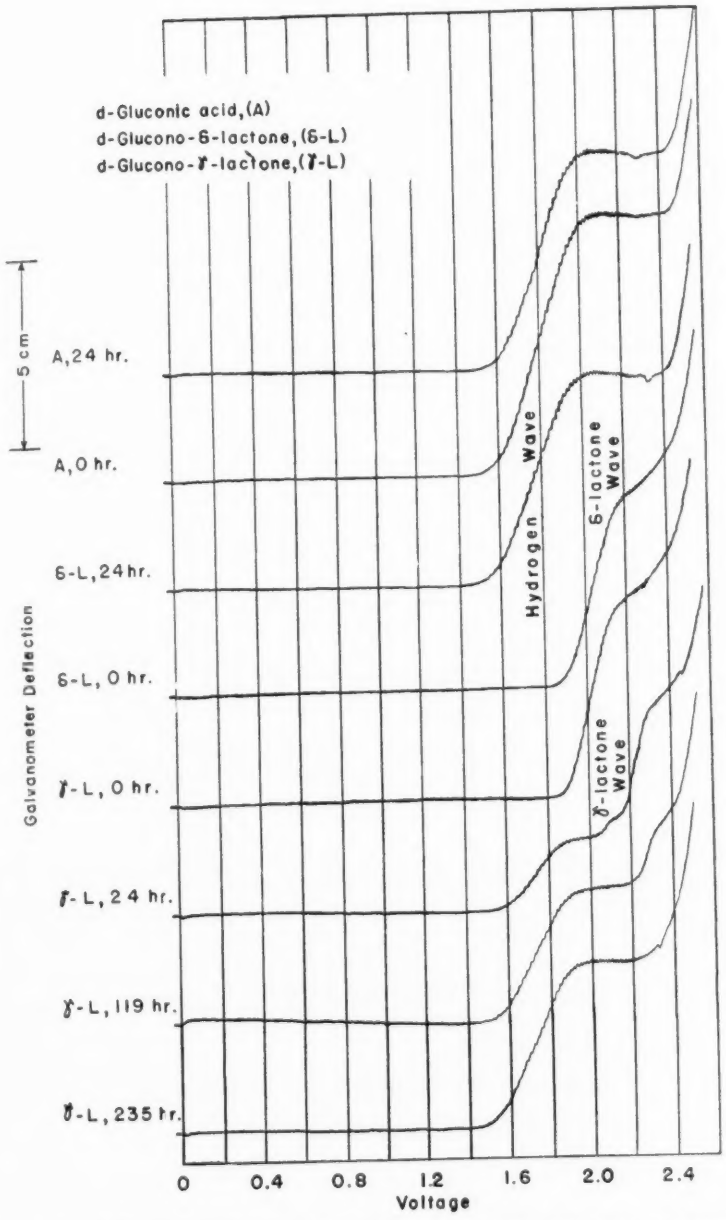



FIGURE 1.—*Polarograms for 0.01 M solutions of d-gluconic acid, d-glucono-δ-lactone, and d-glucono-γ-lactone in 0.05 M lithium chloride.*

These curves may be compared with those of figure 9, which are for the same compounds in 0.1 *M* tetraethylammonium chloride.

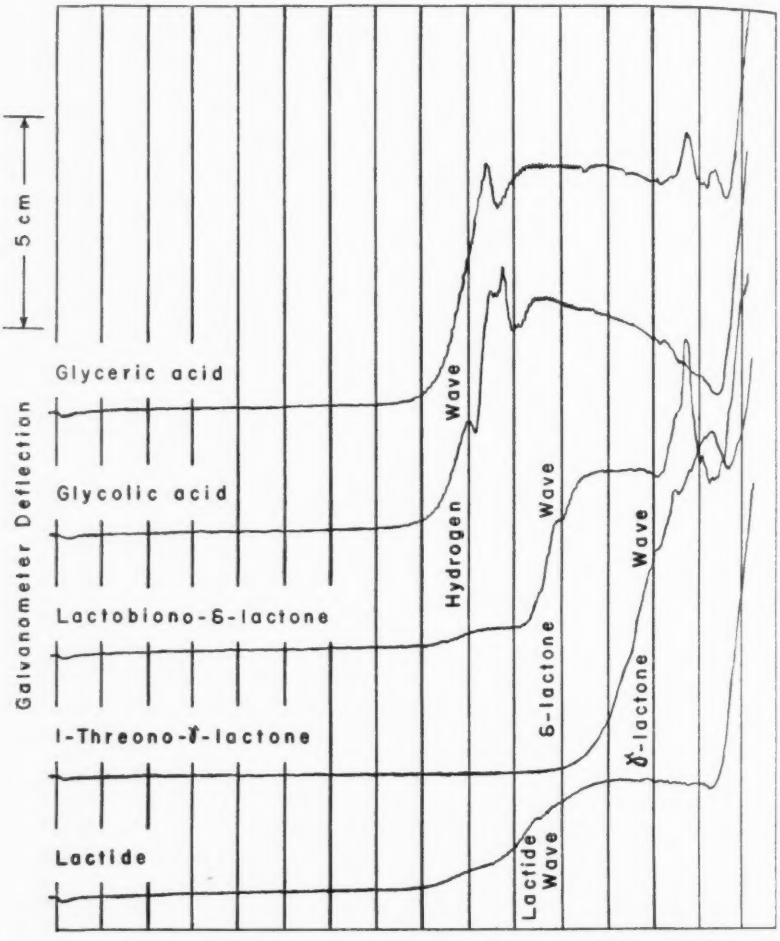



FIGURE 2.—*Polarograms for freshly mixed 0.01 M solutions of glyceric acid, glycolic acid, lactobiono-δ-lactone, l-threono-γ-lactone, and lactide in 0.1 M tetraethylammonium chloride.*

## III. APPARATUS AND PROCEDURE

### 1. ELECTRIC CIRCUIT

The polarograph used was the type VIII instrument of V. & J. Nejedlý, Prague, Czechoslovakia, for photographic recording of current-voltage curves. The galvanometer circuit, shown in figure 3, includes an Ayrton-Mather universal shunt, labeled *sensitivity control*, which was supplied with the instrument. The circuit was improved by two modifications, labeled *compensating resistor* and *constant-deflection* circuit.

The compensating resistor is a five-dial decade resistance box, inserted between the polarograph and the universal shunt, which may be adjusted so that the resistance of the galvanometer circuit, viewed from the polarograph, is substantially independent of the setting of the shunt. With this arrangement, the galvanometer sensitivity may be varied without causing any appreciable variation in the external resistance. In some instances this is of importance, since the appearance of certain types of maxima on the current-voltage curve may be altered by changes in external resistance [2, 3]. Throughout this investigation the compensating resistor was adjusted so that the resistance of the galvanometer circuit between the terminals which connect the galvanometer to the polarograph was 1,498 ohms.

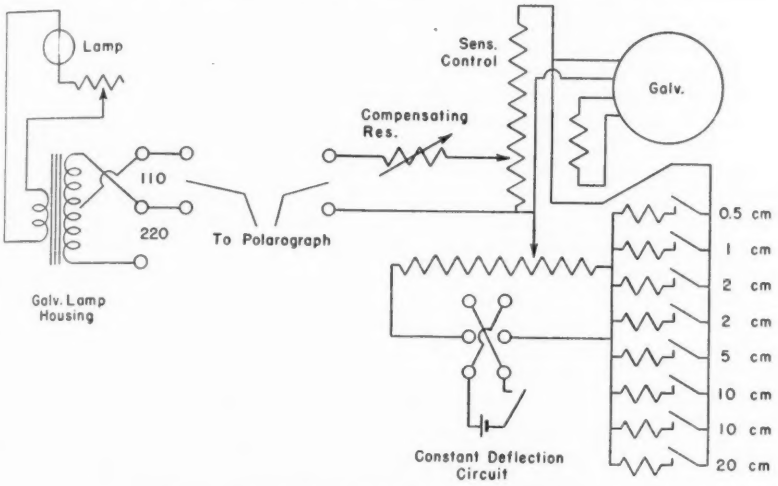



FIGURE 3.—*Auxiliary circuits for polarograph.*

The constant-deflection circuit consists of a 1.5-v flashlight cell and a high-resistance network designed to provide a convenient means of altering the apparent rest point of the galvanometer when several curves are recorded on a single sheet of photographic paper. The resistances within this network were of the order of megohms, so that their presence had no detectable effect on the deflections of the galvanometer produced by currents from the polarograph.

The current sensitivity of the galvanometer, including the universal shunt and compensating resistance in the circuit, was measured [3] for the constant-circuit resistance of 1,498 ohms, at different settings of the universal shunt, with a scale at the same distance from the galvanometer (1 m) as the recording paper was during the polarographic measurements. The current sensitivity used throughout this investigation was $6.44 \times 10^{-7}$ amp/mm/m, which was obtained with the universal shunt set at 1/300.

## 2. ELECTRODES

A constant-level, dropping-mercury electrode of the type described by Mueller [4] was used for the measurements of the *d*-gluconolac-

[3] These measurements were kindly made by D. Ramaley of the Electricity Division of this Bureau.

tones, shown in figures 4 and 5, for the investigation of lactic acid and *d*-lyxono-γ-lactone, and for obtaining a few duplicate curves for *d*-α-glucoheptono-γ-lactone and *d*-β-glucoheptono-γ-lactone. For all other measurements the electrode consisted of a Jena glass capillary, supplied with the instrument, sealed to an ordinary 250-ml soft-glass separatory funnel. With an electrode of this type the height of the mercury surface above the tip is not constant, so that the drop rate is not strictly uniform. However, as the amount of mercury issuing from the capillary per minute is very small, the drop rate changes very slowly. Mercury was added to the reservoir from time to time so that the greatest variation in the mercury head was 5 mm in 24 cm. When the electrodes were not in use, the capillary tips were immersed in mercury and the stopcocks were closed.

Data obtained on the characteristics of these two capillaries included the mass of mercury issuing from the tip per second in air, and the drop time measured under a variety of conditions, namely: in air, in air-saturated distilled water, and in 0.1 *M* tetraethylammonium chloride. In these measurements the dropping electrode was directly connected, electrically, to a pool of mercury in the bottom of the vessel containing the solution. Values were also obtained for the drop rate of the electrode in 0.1 *M* tetraethylammonium chloride solutions with various potentials applied to a polarograph cell. As has been reported in the literature, the drop rate of both capillaries was very rapid when the potential was increased above about 2 v. Above about 2.5 v the drop rate became progressively more erratic.

This increase in the drop rate is believed to be the cause of the apparent decrease in the diffusion current for the reduction of hydrogen ion at the higher potentials. Fluctuations in the drop rate are also believed to be responsible, at least in part, for the erratic variations of the diffusion currents occasionally noticed and shown in many of the curves selected for reproduction. The mass rate in air and drop rates in air, distilled water, and 0.1 *M* tetraethylammonium chloride at zero applied voltage for the Mueller capillary were 4.46 mg/sec, 33.6 sec/drop, 6.8 sec/drop, and 6.0 sec/drop, respectively; and for the Jena capillary at the lowest pressure were 2.42 mg/sec, 18.7 sec/drop, 3.0 sec/drop, and 2.8 sec/drop; and at the greatest hydrostatic head were 2.52 mg/sec, 17.7 sec/drop, 2.9 sec/drop, and 2.7 sec/drop, respectively.

The anode potential in solutions which contain chloride ion is, in general, fairly stable. The anode potential relative to a normal calomel electrode with liquid junction was measured in two environments before, during, and after the taking of a polarogram. In the 0.1 *M* lithium chloride solution the anode potential is $+0.061 \pm 0.001$ v; in the 0.1 *M* tetraethylammonium chloride solution it is $+0.055 \pm 0.005$ v. In both cases the anode is positive with respect to the normal calomel electrode. The potentials reported in this paper are with respect to the mercury anode but may be referred to the normal calomel electrode, if desired, by means of these values.

### 3. PREPARATION OF THE SOLUTIONS FOR POLAROGRAPHIC MEASUREMENT

Since many of the compounds studied in this investigation are subject to hydrolysis and other changes when in solution, a technique

was developed by which the first polarogram was started within 2 to 5 minutes after the first wetting of the solid compound. The vessels used to contain the solutions were of the Erlenmeyer type in which a pool of pure mercury served as the anode. The purified salt [4] to be used as the environmental electrolyte was dissolved in distilled water in a fritted quartz crucible and filtered, with suction, into a quartz vessel. The chloride in a weighed amount of the stock solution was determined gravimetrically as silver chloride. From this stock solution a 0.1 molal solution was made up in quartz [5] as needed.

Ordinarily, 9 ml of the 0.1 molal solution containing the desired environmental salt was placed in the cell, and oxygen was eliminated by bubbling through the solution commercial nitrogen, freed from oxygen by passage through an electrically heated furnace charged with copper. After about 30 minutes, when oxygen had been removed from the cell, 1 ml of a freshly prepared solution, containing the desired quantity of the compound in oxygen-free water, was added and the polarogram started. The times of wetting the sample, introducing the solution into the cell, and starting the polarogram were noted. After the polarogram was completed, the cell was stoppered and the solution was allowed to stand at room temperature. Whenever solutions were investigated more than 1 day after mixing, they were protected from molds by the addition of several drops of xylene. Control experiments showed that the addition of xylene had no effect on the polarograms.

### 4. MEASUREMENT OF POLAROGRAMS

The potentials of the inflection points of the waves were measured, and are given with respect to the mercury anode. In the absence of a maximum, the inflection point of a symmetrical wave with a steep slope may be located with precision; but if the slope is not steep, the exact location of the inflection point becomes doubtful. In the presence of a maximum or when a wave is not symmetrical about its inflection point, as is the case when two waves are partially merged, the estimate may be uncertain by 0.05 v or more. Because of the uncertainty in the measurement and the variation of the potential with the experimental conditions, no attempt has been made to correct for the IR drop in the solutions. In the tetraethylammonium chloride environment, the polarograms for the acids show a pronounced pointed maximum, associated with the hydrogen wave, which is completed at potentials considerably less than those necessary to develop the diffusion current. Such a maximum is shown, for example, in figure 2. In many cases, though the wave height decreases when the solution is allowed to stand, the height of the maximum decreases more rapidly, so as to give the appearance of two waves with inflection points at nearly the same potential. On further decrease of wave height there ceases to be any evidence that two waves are involved (see fig. 10). With several solutions prepared from lactones, the hydrogen wave develops on standing and the reverse phenomena are observed, that is, a single small wave as it grows takes on the appearance of two waves, one of which, on continued growth, shows a small pointed maximum (see figs. 5 and 8).

[4] A method for the purification of tetraethylammonium chloride will be published later.

[5] In Pyrex cells at a sensitivity of $\frac{1}{10}$, a slight alkali metal wave which increased definitely with time could be detected in 0.1 molal solution.

Since the reductions leading to the polarographic activity of the compounds of the present investigation are probably not reversible, the apparent potentials of the inflection points may be expected to change with changes in concentration and environment, by amounts several times as large as could be explained on the basis of experimental error. In the tetraethylammonium chloride environment used in our later work, the hydrogen and lactone waves occur at more negative potentials than in the lithium chloride environment used in our earlier work.

Müller [1] has discussed the effect of acidity and buffers on the appearance and position of waves due to both reversible and irreversible reactions in which hydrogen ion is involved. In connection with our work, it is sufficient to point out that when a reaction occurs at the dropping electrode the pH in the vicinity of the electrode may be quite different from that in the bulk of the solution. It will, in general, depend not only on the reaction occurring but also on its rate at any instant; and, as a result, the position and form of the resulting polarographic wave will be affected by the acidity of the main body of the solution, the buffering capacity of the environment, the characteristics of the capillary, and the concentration of the reacting substance.

The wave heights were estimated with the aid of a pair of dividers as the net vertical displacement. In many cases the waves were well defined and the heights could be determined within 5 percent. In other cases, especially with the waves in an environment of 0.1 *M* tetraethylammonium chloride at potentials more negative than −2.5 v, the diffusion currents were erratic and often the appearance of the whole wave was distorted by this behavior. Naturally, the estimation of the height of such a wave is very uncertain and the error may amount to as much as 25 percent. In discussing the results we have ignored the implications of the Ilkovič equation, which correlates the diffusion current with the product of the concentration and the number of electrons involved per molecule, because the reductions appear to be irreversible and the drop-rate of the capillary changes rapidly with potential in the region where most of the waves occur.

## IV. APPLICATION OF THE POLAROGRAPHIC METHOD TO THE STUDY OF THE FORMATION AND SPLITTING OF LACTONES

In previous publications [5] it has been shown that sugars which have like configurations for the first five carbon atoms exhibit similar mutarotation reactions and establish similar equilibrium states involving the pyranose, furanose, and open-chain modifications.[6] Likewise aldonic acids which have similar configurations resemble one another in that they establish equilibrium states which involve similar proportions of their gamma and delta lactones. The formation and splitting of aldonic lactones have been investigated in concentrated solutions [7], but very little is known about these reactions in dilute aqueous solution. In fairly concentrated solutions, delta lactones are formed and split much more rapidly than the corresponding gamma lactones. For example, when *d*-gluconic acid is

[6] Recently Cantor and Peniston [6] have shown that the polarographic method may be used to estimate the amounts of the open-chain modification present in sugar solutions.

dissolved in water, the delta and gamma lactones are formed simultaneously; but, since the delta lactone is formed more rapidly than the gamma, its concentration reaches a maximum in 4 or 5 hours and then decreases as more of the sugar acid is converted to the gamma lactone. When *d*-glucono-δ-lactone is dissolved in water, it is hydrolyzed rapidly, and in the course of several hours an equilibrium is established with the free acid, while the gamma lactone is formed slowly at the expense of both the free acid and the delta lactone. When *d*-glucono-γ-lactone is dissolved in water, it is hydrolyzed slowly, and in the course of many days an equilibrium is established with the acid and delta lactone. All aldonic acids form this type of equilibrium, whose position depends on the experimental conditions and on the structure and configuration of the aldonic acid. Concentrated equilibrated solutions of aldonic acids which have the mannonic, gulonic, allonic, or talonic configuration usually contain large quantities of the gamma lactones, which can be crystallized readily. Concentrated solutions of *d*-gluconic acid contain substantial quantities of both the delta lactone and the free acid and yield either *d*-glucono-δ-lactone or *d*-gluconic acid, according to whether crystallization is conducted at high or low temperatures. Thus, it is apparent that concentrated solutions of the aldonic acids in equilibrium contain delta and gamma lactones in substantial quantities. Since the lactones react with water, the proportion of lactone in the acid-lactone mixture depends on the concentration and on the equilibrium constants of the acid-lactone interconversion reactions. Thus, information concerning the composition of the equilibrium mixture in dilute aqueous solutions of the aldonic acids is of both theoretical and practical value. Although the quantitative results obtained by application of the polarographic method to the problem appear to be somewhat limited, nevertheless they reveal considerable information.

Figures 4 and 5 show the changes in the polarograms of 0.01 *M* *d*-glucono-δ-lactone and 0.01 *M* *d*-glucono-γ-lactone in 0.1 *M* tetraethylammonium chloride solutions on standing. From the heights of the waves at various times, curves may be constructed to show changes in the compositions of the solutions.[7] A number of these curves are shown in figures 6 and 7.

The freshly prepared solution of *d*-glucono-δ-lactone did not give a hydrogen wave, but after the solution had stood for only a few minutes a hydrogen wave appeared and increased in height while the delta lactone wave decreased until, after 3.3 hours, it was not visible. Inasmuch as the delta lactone waves for *d*-glucono-, *d*-mannono-, *l*-rhamnono-, and lactobiono-δ-lactone disappear completely in the course of several hours, the equilibrium states for 0.01 *M* solutions of the corresponding acids do not appear to contain appreciable quantities of the delta lactones. The absence of the delta lactone wave in 0.01 *M* solution at equilibrium is surprising, since *d*-glucono-δ-lactone crystallizes readily from concentrated aqueous solutions of *d*-gluconic acid. The polarograms for dilute solutions prepared from other aldonic acids, after standing for sufficient time to permit establishment of equilibrium between the acid and the delta lactone, fail to show definite waves corresponding to the delta lactones. With a few of the

[7] Velocity constants for the lactone formation and cleavage reactions may be calculated from the wave heights, but these are not included because it seemed desirable to make measurements at different acidities and under more closely controlled conditions before calculating velocity constants.

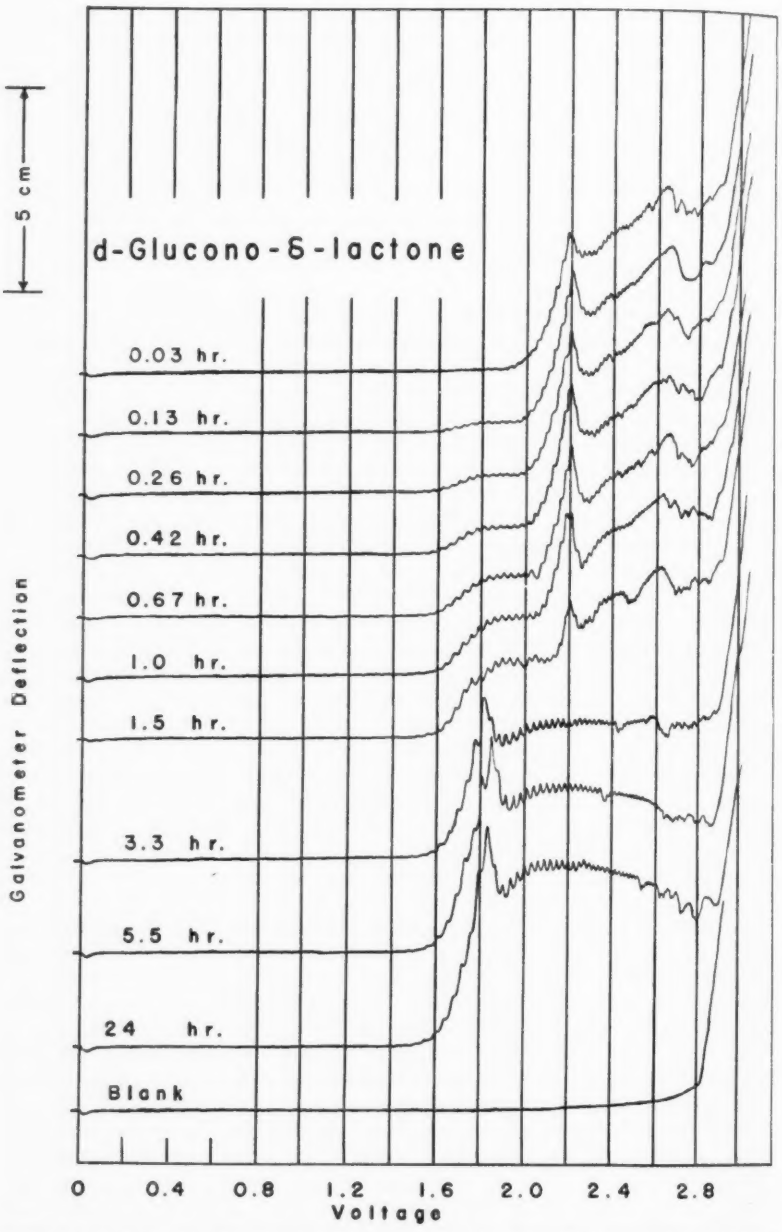



FIGURE 4.—*d-Glucono-δ-lactone, 0.01 M, in 0.1 M tetraethylammonium chloride.*

The times given are measured from the first wetting of the solid to the starting of the polarogram. The polarograph was set to increase the potential 0.536 v/min.

The curves were made using a freshly recrystallized sample and the constant-level capillary. As a result they are comparable only qualitatively with those for the same compound shown in figure 9.

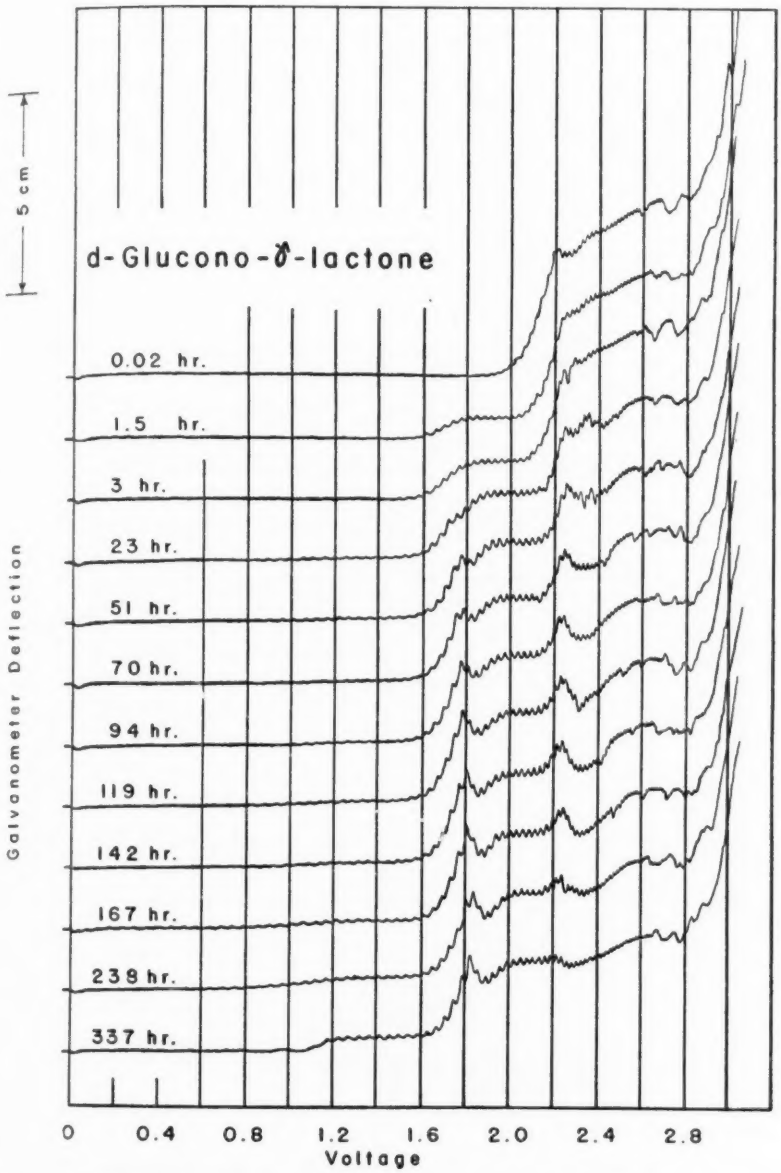



FIGURE 5.—*d-Glucono-γ-lactone, 0.01 M, in 0.1 M tetraethylammonium chloride.*

The curves were made using a freshly recrystallized sample and the constant-level capillary. As a result they are comparable only qualitatively with those for the same compound in figure 9.

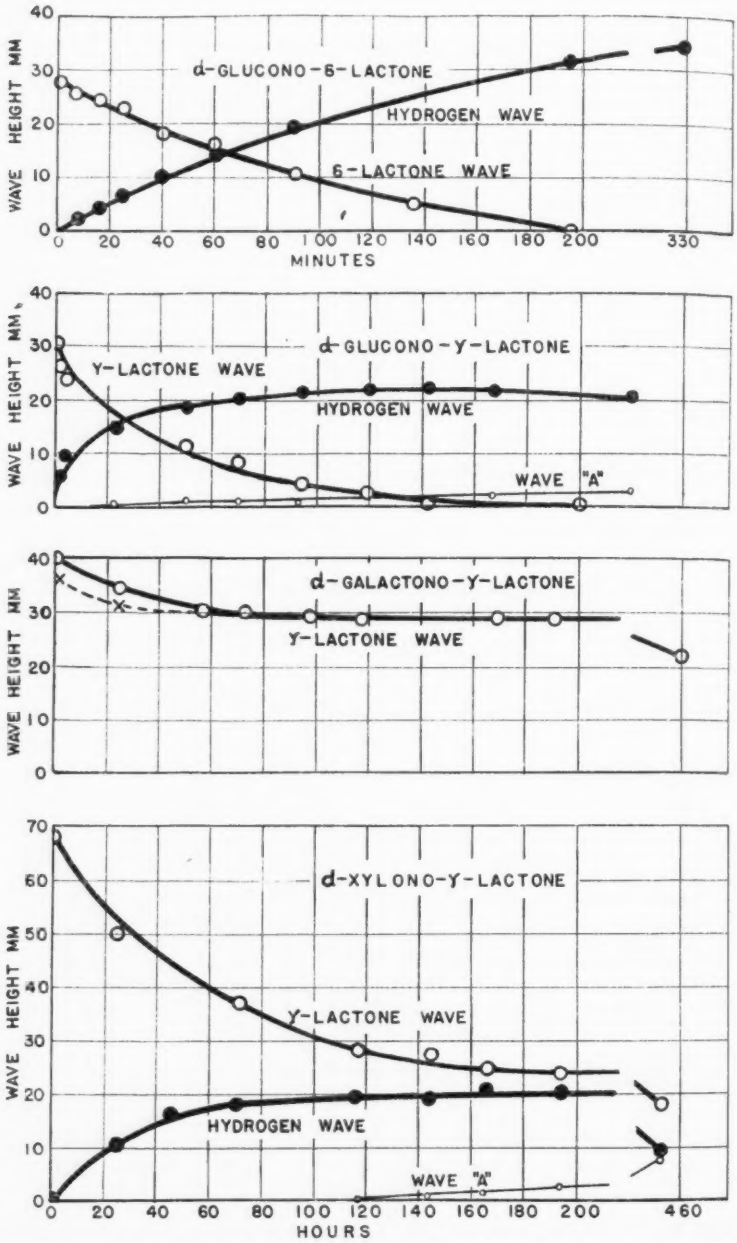



FIGURE 6.—*Curves which show the change of wave height with time, at room temperature, for 0.01 M solutions of d-glucono-δ-lactone, d-glucono-γ-lactone, d-galactono-γ-lactone, and d-xylono-γ-lactone in 0.1 M tetraethylammonium chloride.*

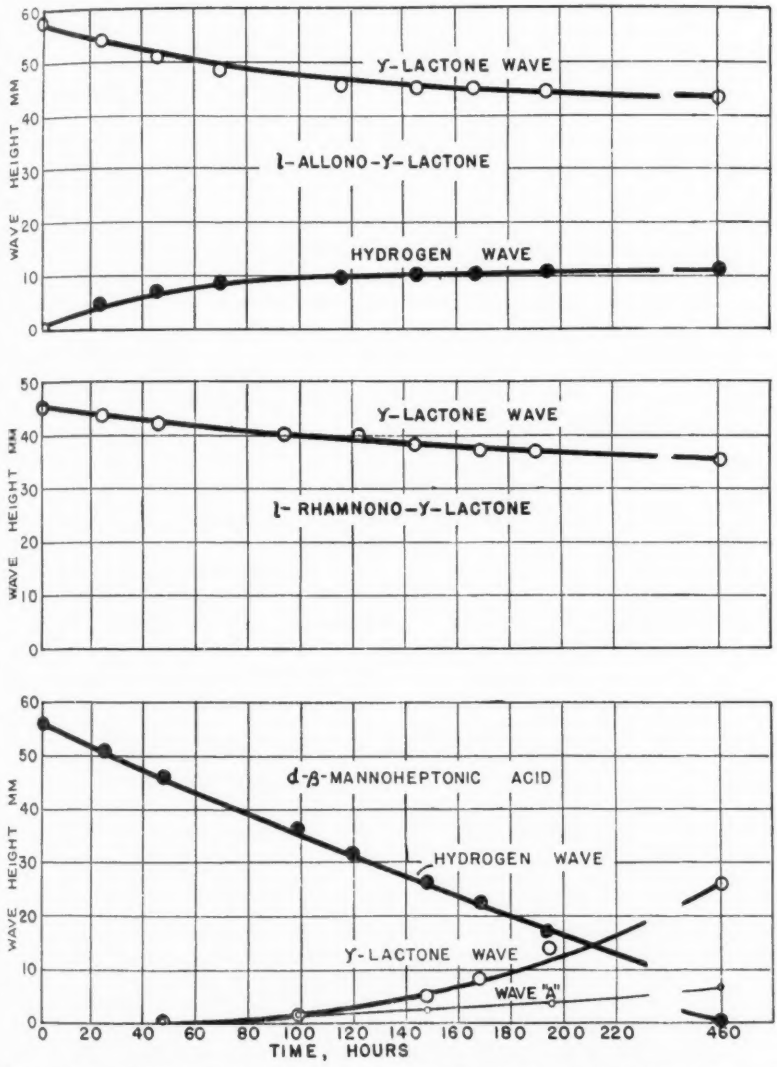



FIGURE 6 (continued).—*Curves which show the change of wave height with time, at room temperature, for 0.01 M solutions of l-allono-γ-lactone, l-rhamnono-γ-lactone, and d-β-mannoheptonic acid in 0.1 M tetraethylammonium chloride.*

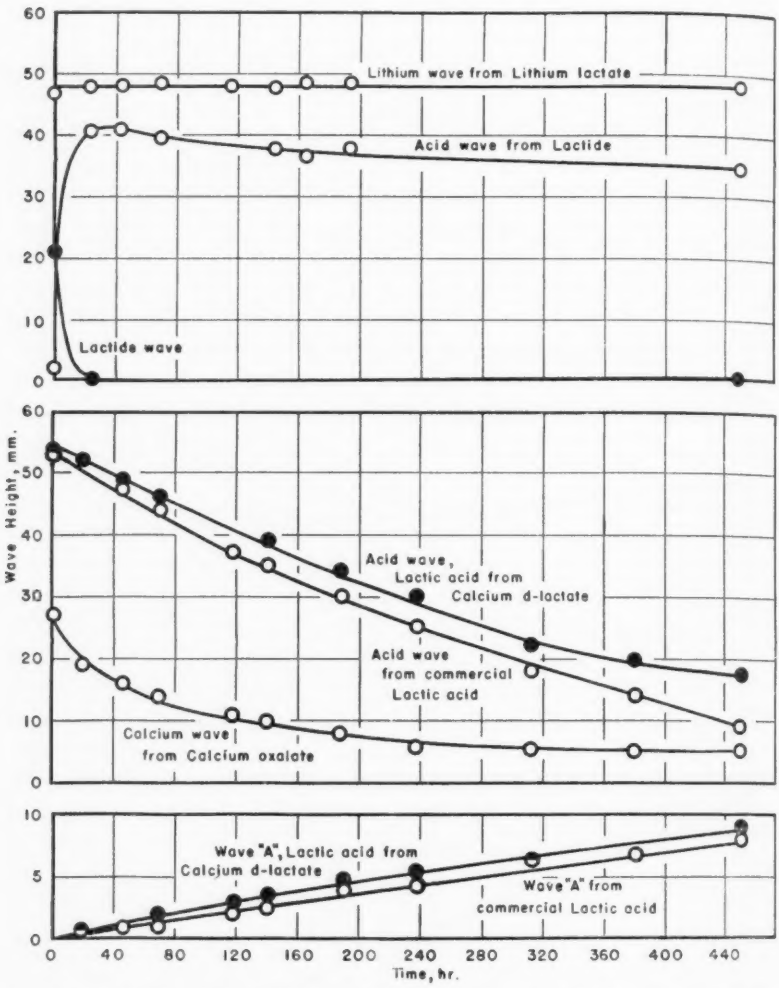

Lithium wave from Lithium lactate
Acid wave from Lactide
Lactide wave
Wave Height, mm.
Acid wave, Lactic acid from Calcium d-lactate
Acid wave from commercial Lactic acid
Calcium wave from Calcium oxalate
Wave "A", Lactic acid from Calcium d-lactate
Wave "A" from commercial Lactic acid
Time, hr.

FIGURE 7.—*Curves of wave height as a function of time for 0.01 M solutions of lactic acid liberated from calcium d-lactate, commercial lactic acid, lithium lactate, and lactide in 0.1 M tetraethylammonium chloride.*

acids in dilute aqueous solutions, inflections in the polarograms were observed which might have been caused by delta lactones, but these waves were small and doubtful.

The absence of an appreciable quantity of the delta lactone in the equilibrium mixture is in marked contrast to the presence of the gamma lactone. Every gamma hydroxy acid studied, after standing in dilute aqueous solution, developed a polarographic wave in the region characteristic of the gamma lactone. The heights of these waves increased on standing and in some cases approached the heights of the waves obtained from solutions prepared from the corresponding gamma lactones which had stood for the same length

of time. (See the curves for *d*-α-guloheptonic acid and its gamma lactone, fig. 12.)

The polarograms obtained for the solutions prepared from the free acids gave, in every case, a large hydrogen wave in the range from −1.68 to −1.88 v. When the solution containing a sugar acid was allowed to stand in the reaction vessel, the height of the hydrogen wave gradually decreased and a new wave appeared between −1.1 and −1.2 v. In the early stages of the investigation the decrease in the height of the hydrogen wave was considered as an indication of the formation of lactones or other esterlike compounds. Measurements made with solutions which had stood in the presence and in the absence of oxygen and mercury indicate that the decrease in the height of the hydrogen wave is caused in part by dissolved oxygen in the presence of the mercury and the formation of some substance which gives the −1.2-v wave. For convenience, in future discussion this wave will be designated wave *A*.[8] Unfortunately, the reaction of the sugar acids with the mercury in the cell disturbs the acid-lactone equilibrium and thus complicates the interpretations of the curves. This factor was not recognized until after most of the measurements had been completed, and consequently the experimental method was not changed to eliminate it.

The polarographic behavior of the gamma lactones in dilute aqueous solution is illustrated by the curves for *d*-glucono-γ-lactone, *d*-galactono-γ-lactone, *d*-xylono-γ-lactone, *l*-allono-γ-lactone, and *l*-rhamnono-γ-lactone, (fig. 6). The relatively more rapid changes in the heights of the waves for *d*-glucono- and *d*-xylono-γ-lactone are in contrast to the slower change in the height of the wave for *l*-rhamnono-γ-lactone. Most of the gamma lactones studied are hydrolyzed at rates which lie between these extremes and give curves such as those shown for *l*-allono- and *d*-galactono-γ-lactone.

The curve for *d*-galactono-γ-lactone illustrates another interesting aspect of the work. It will be observed that the slope of the curve which represents the height of the lactone wave is somewhat greater during the first 48 hours than during the period which follows. Close examination of the polarograms taken at 0 and 24 hours (fig. 10) reveals the presence of a partially merged −2.3-v wave, which disappeared in 48 hours. The rate of disappearance for the wave is less than the rate of change for the delta lactones investigated, but nevertheless this wave may have been caused by the unknown delta lactone. It is of further interest that the freshly prepared solution of *d*-α-mannoheptono-γ-lactone gave a similar −2.3-v wave which disappeared slowly, and that solutions of *d*-α-glucoheptono-γ-lactone, of *d*-α-guloheptonic acid, and of *d*-β-guloheptonic acid gave, on standing, small waves at potentials near −2.3 v (figs. 11 and 12). For convenience these waves are designated as "−2.3-v" waves. It is well known that the sugar acids in aqueous solution frequently give complex amorphous products of unknown structure, and it is entirely possible that these products are associated with the polarographic waves which have been noted; but further investigation is

[8] Although wave *A* appears whenever acid, mercury, and oxygen are in contact, the reaction does not seem to be as simple as is indicated by the eq [8]

$$2\,Hg + O_2 \rightarrow Hg_2^{++} + O_2^{--}$$

since in the absence of mercury a 0.001 *M* gluconic acid solution in 0.1 *M* lithium chloride seems to react with oxygen to produce a substance giving a small wave at −1.25 v and a marked increase in the height of the hydrogen wave. This phase of the subject warrants further study.

necessary to provide a satisfactory explanation for these −2.3-v waves.

Table 1 gives the heights of the polarographic waves correlated with the free acids, the gamma, and delta lactones.

TABLE 1.—*Heights of some of the identified polarographic waves observed with 0.01 M solutions in 0.1 M tetraethylammonium chloride (in millimeters at sensitivity 1/300)*

| Substance | Acid wave (−1.7 to −1.8 v) | | | Wave *A* | Gamma lactone wave (−2.2 to −2.7 v) | | Delta lactone wave (−2.2 to −2.3 v) | |
|---|---|---|---|---|---|---|---|---|
| | Initial | Maximum | Final [a] | Final [a] | Initial | Final [a] | Initial | Final [a] |
| *Acids:* | | | | | | | | |
| Glycolic | 53 | 72 | 39 | 2 | | | | |
| Lactic | 53 | 53 | 9 | 9 | | | | |
| Glyceric | 50 | 53 | 26 | 2 | | | | |
| *d*-Gluconic | 55 | 55 | 12 | 7 | 0 | 1 | | |
| *d*-Galactonic | 64 | 64 | 0 | 6 | 0 | 20 | | |
| *d*-Talonic | 40 | 40 | 0 | 3 | 0 | 24 | | |
| *d*-α-Guloheptonic | 53 | 53 | 0 | 4 | 0 | [b] 33 | | |
| *d*-β-Guloheptonic | 57 | 57 | 0 | 5 | 0 | 18 | | |
| *d*-β-Mannoheptonic | 55 | 55 | 0 | 6 | 0 | 26 | | |
| *Gamma lactones:* | | | | | | | | |
| *d*-Erythrono- | 0 | 4 | 4 | | 60–70 | 60–70 | | |
| *l*-Threono- | | | | 1 | 70 | 50 | | |
| *l*-Arabono- | 0 | 1 | 0 | 3 | 60 | 40 | | |
| *l*-Ribono- | 0 | 2 | 2 | 1 | 61 | 40 | | |
| *d*-Xylono- | 0 | 20 | 10 | 7 | 68 | 18 | | |
| *d*-Lyxono- | | | | 2 | 60 | 30 | | |
| *l*-Rhamnono- | | | | | 45 | 35 | | |
| *d*-Glucono- | 0 | 20 | 18 | 6 | 40 | 1 | | |
| *d*-Galactono- | 0 | 1 | 0 | 2 | 36 | 22 | | |
| *d*-Mannono- | 0 | 3 | 3 | | 50 | 50 | | |
| *d*-Talono- | 0 | 8 | 8 | | 50 | ? | | |
| *d*-Gulono- | | | | 1 | 50 | 38 | | |
| *l*-Allono- | 0 | 11 | 11 | | 58 | 43 | | |
| *d*-α-Galaheptono- | 0 | 1 | 1 | | 45 | 45 | | |
| *d*-α-Glucoheptono- | 0 | 13 | 13 | | 45 | 45 | | |
| *d*-β-Glucoheptono- | | | | | 57 | 47 | | |
| *d*-α-Guloheptono- | | | | 2 | ? | ? | | |
| *d*-α-Mannoheptono- | 0 | 7 | 7 | | 35 | 27 | | |
| *d*-β-Mannoheptono- | | | | 1 | 53 | 32 | | |
| *Delta lactones:* | | | | | | | | |
| *l*-Rhamnono- | 0 | 39 | 36 | | 0 | ? | 35 | 0 |
| *d*-Glucono- | 0 | 55 | 11 | 6 | 0 | 8 | 33 | 0 |
| *d*-Mannono- | 0 | 29 | 8 | 4 | 0 | 12 | 50 | 0 |
| Lactobiono- | 4 | 53 | 53 | | | | 36 | 0 |
| Lactide | 5 | 41 | 35 | | | | | |

[a] Values obtained after approximately 450 hours at room temperature.
[b] Total height of what appears to be two waves, at −2.3 and −2.6 v.

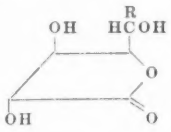
## V. EFFECT OF CONFIGURATION AND STRUCTURE ON THE REDUCTION POTENTIALS OF THE GAMMA LACTONES

One of the objects of the present investigation was to ascertain whether a relation could be found between the configurations of the lactones and their reduction potentials. The different configurations for carbons 2, 3, and 4 of the gamma lactones give rise to eight isomers consisting of four pairs of enantiomorphs. Inasmuch as the enantiomorphs have like chemical properties and may be expected to have identical polarographic activity, the gamma lactones may be classified in four groups corresponding in configuration to the lactones of xylonic, ribonic, arabonic, and lyxonic acids. Since carbon 4 in *l*-threono-γ-

lactone and in *d*-erythrono-γ-lactone does not carry a side chain, these lactones may be classified with equal propriety in the xylonic and the lyxonic groups, respectively, or in the arabonic and the ribonic groups. In table 2 they have been placed in the former groups.

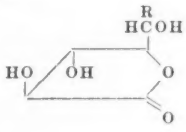
TABLE 2.—*Inflection points for gamma lactones* [a]

Xylonic configuration:



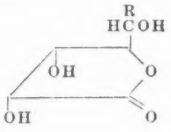
| *Gamma lactone* | *Volts* |
|---|---|
| Threono- | −2.54 |
| Xylono- | −2.48 to −2.56 |
| Glucono- | −2.15 to −2.30 |
| β-Glucoheptono- | −2.53 |

Arabonic configuration:



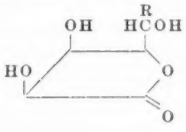
| *Gamma lactone* | *Volts* |
|---|---|
| Arabono- | −2.60 |
| Galactono- | −2.62 |
| α-Mannoheptono- | −2.65 |
| β-Guloheptono- | −2.6[b] |

Ribonic configuration:



| *Gamma lactone* | *Volts* |
|---|---|
| Ribono- | −2.50 |
| Allono | −2.52 |
| Talono- | −2.50 |
| α-Guloheptono- | −2.55 |
| β-Mannoheptono- | −2.50 to −2.56 |

Lyxonic configuration:



| *Gamma lactone* | *Volts* |
|---|---|
| Erythrono- | −2.65 |
| Lyxono- | −2.6 |
| Mannono- | −2.65 |
| Rhamnono- | −2.68 |
| Gulono- | −2.60 |
| α-Galaheptono- | −2.65 |
| α-Glucoheptono- | −2.56 to −2.64 |

[a] Polarographic waves obtained with 0.01 *M* solutions of gamma lactones in 0.1 *M* tetraethylammonium chloride.

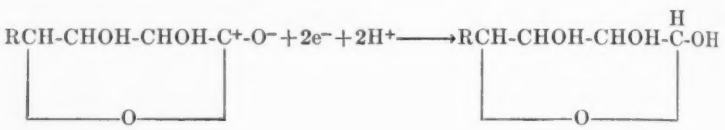
[b] This value was obtained by measurement of a lactone solution prepared from the corresponding acid.

In table 2 the gamma lactones are listed in four groups according to configuration. The potential of the inflection point of the polarographic wave given by each lactone may be considered as a measure of the ease of reduction of that compound. With the possible exception of the values for *d*-α-glucoheptono-γ-lactone and *d*-glucono-γ-lactone, the potentials obtained for substances of like configuration show surprisingly small differences. In fact, the differences in the potentials for substances of like configuration in the tetronic, pentonic, hexonic, and heptonic series are for the most part within the experimental error of the measurements. When a solution of *d*-α-glucoheptono-γ-lactone is allowed to stand, the potential shifts to −2.64 v, in agreement with the potentials obtained for other members of the lyxonic group. The reason for the low potential found for *d*-glucono-γ-lactone is not known.

An examination of the reduction potentials in relation to the *cis-trans* arrangements of the groups attached to the lactone ring reveals that lactones in which the OH of carbon 2 and the terminal $CH_2OH$ group lie on the same side of the ring (*cis*) give reduction potentials in the range from −2.6 to −2.7 v, whereas lactones in which these groups

lie on opposite sides of the ring (*trans*) give reduction potentials in the range from −2.2 to −2.55 v when the substances are in the tetraethylammonium chloride environment.

Supposedly the reduction of a lactone, represented by the equation given below, involves the addition of two electrons to carbon 1 followed by the acquisition of two protons, and the reduction potential can be considered as a function of the tendency of the lactone to exist as such, rather than to take up electrons.




Gamma lactone Aldose

Since *d*-erythronolactone and *l*-threonolactone, for example, differ only in the configuration of carbon 3, the difference in their reduction potentials must originate in the spatial arrangement of the hydroxyls and hydrogens. In other words, the relative positions of the hydroxyl groups and hydrogen atoms influence the electronic stability of the lactone group. The effect of the locations of the hydroxyl groups may be explained by assuming that the lactone structure is stabilized by the formation of hydrogen bonds between the protons of hydroxyl groups and the carbonyl oxygen. Supposedly the hydroxyl on carbon 2 forms a hydrogen bond with the carbonyl oxygen; when the hydroxyl of either carbon 3 or carbon 5 (or both) lies on the same side of the ring as the hydroxyl of carbon 2, the hydrogen of either of these hydroxyls (or both) would also be attracted to the negative carbonyl oxygen and would tend further to stabilize the lactone group. But if the hydroxyls of carbons 3 and 5 lie on the opposite side of the ring from the hydroxyl of carbon 2, the attraction of their protons for the carbonyl oxygen would be exerted in the opposite direction and would tend to weaken the lactone structure. Furthermore, the hydroxyls of carbons 2 and 5 are in more favorable positions for coordination with the carbonyl oxygen than the hydroxyl of carbon 3, and hence their relative positions in space would be of more importance than the position of the hydroxyl of carbon 3 in determining the stability of the lactone. In agreement with this concept, the highest reduction potentials are obtained when the hydroxyls of carbons 2, 3, and 5 all lie on the same side of the ring, and hence in favorable positions for coordination with the carbonyl oxygen. The next highest reduction potentials are obtained when the hydroxyls of carbons 2 and 5 are favorably located, and the lowest reduction potentials are obtained when the hydroxyl of carbon 2 is on one side of the lactone ring and the hydroxyls of carbons 3 and 5 are on the other side.

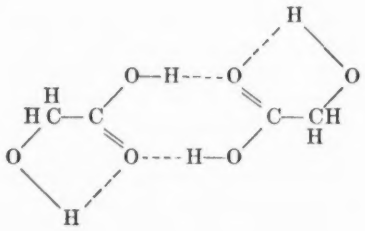
## VI. CHARACTERISTIC FEATURES OF THE POLAROGRAMS FOR THE VARIOUS SUBSTANCES

Since only a few of the polarograms made in the course of this investigation can be reproduced in this paper, an attempt has been made to describe briefly the characteristic features of the curves obtained. In comparing the results it should be remembered that the lower

acids—glycolic, lactic, and glyceric—do not form lactones but form condensation products of the lactyllactic acid and lactide types. They also form more complex polymers which have not been included in the present investigation. The tetronic acids form stable gamma lactones and show little tendency to form condensation products of the lactide and lactyllactic acid types. They differ from the higher aldonic acids in that they cannot form delta lactones and in that on carbon 4 they have two hydrogen atoms, symmetrically located with respect to the lactone ring, in place of a single hydrogen and a side chain. Although the pentonic acids are capable of forming delta lactones in addition to the gamma lactones and condensation products, the polarograms for the pentonic acids and their gamma lactones fail to show the presence of detectable quantities of delta lactones. In the methyl pentonic and hexonic groups, several delta lactones are known, and we have determined their polarographic behavior. Most of the compounds used in these measurements were prepared in the Bureau's laboratories by the methods cited in the reference given after the name of the compound; other sources of material are indicated in footnotes.

### 1. GLYCOLIC ACID [1]

A 0.01 *M* solution of glycolic acid in 0.1 *M* tetraethylammonium chloride showed only a −1.8-v hydrogen wave with a pointed maximum (fig. 2). During the course of 24 hours, the height of the wave increased from 53 mm to a maximum of 72 mm. Since the increase in the hydrogen wave is evidence of a change in structure, it seems probable that part of the acid hydrogen in the freshly prepared solution is bound in some manner. In this connection, it is noteworthy that glycolic acid exists in two crystalline forms [9]; the one used in this investigation melts at 80° C, the other melts at 63° C. Ohle [10] has suggested that glycolic acid under suitable conditions exists in a dimolecular state represented by the following formula:



A substance having this structure would yield acidic groups on splitting and account for the observed increase in the hydrogen wave.

The solution of glycolic acid after long standing gave a small wave at −2.8 v which appears to be analogous to a similar wave found for lactic acid.

### 2. LACTIC ACID, LACTYLLACTIC ACID, AND LACTIDE

The practical and theoretical importance of lactic acid and its derivatives led to the study of lithium lactate [11], lactic acid liberated from

[1] The glycolic acid was purchased from A. D. Mackay, New York, N. Y.

calcium *d*-lactate,[10] commercial lactic acid containing lactyllactic acid [12], and lactide [13] (fig. 7).

The polarograms of 0.01 *M* lithium lactate in 0.1 *M* tetraethylammonium chloride showed only a lithium wave at −2.44 v, 46 to 48 mm high, with a small pointed maximum. The absence of other waves shows that the lactate ion is not reduced under the conditions used. Measurements were made with lactic acid, freshly prepared from calcium *d*-lactate by the addition of an equivalent quantity of oxalic acid, to compare with measurements made with commercial lactic acid after dilution with water. Except for the effect of traces of calcium arising from the solubility of calcium oxalate, there was no significant difference between the polarograms for the commercial acid and those for the acid liberated from calcium *d*-lactate. As shown in figure 7, the freshly mixed solutions showed hydrogen waves 53 and 52 mm high, which decreased in the course of 453 hours at room temperature to 9 and 17 mm, respectively. At least a portion of this decrease in acid concentration was associated with the appearance of wave *A*, which after 453 hours had grown to 9 and 8 mm.

After 200 hours there appeared in polarograms of both solutions evidence of a wave at about −2.85 v. After 453 hours this wave was 15 mm high at −2.85 v in the solution which contained originally calcium *d*-lactate, and about 40 mm high at −2.80 v in the solution which contained originally commercial lactic acid. This wave, which appears analogous to that observed with glycolic acid, cannot be ascribed to the lactyllactic acid linkage unless its reduction potential is markedly a function of pH and was, as a result, masked in the earlier polarograms by the reduction of the tetraethylammonium ion present in the supporting electrolyte.

Another interesting feature of the study of these two solutions was the behavior of the wave at −2.40 v, due to calcium ion. Although the solution was stirred only for a short time immediately preceding the taking of each polarogram, it is surprising that aging of the precipitated calcium oxalate, as indicated by the change in its solubility, should require 300 hours at room temperature. The magnitude of the change in solubility cannot be considered as proportional to the change in wave height, because the reduction of calcium ion at the dropping mercury electrode is a complex phenomenon giving rise to waves which are not a linear function of the concentration [14].

The results obtained with lactide are of particular interest because they establish the existence of a polarographic wave for the lactide linkage. Lactide is not sufficiently soluble to yield rapidly a 0.1 *M* aqueous solution, and consequently the solution, after dilution in the electrode vessel, was somewhat less than 0.01 *M*. Although the first polarogram (fig. 2) was begun only 7 minutes after the compound was wet with water, hydrolysis had already proceeded sufficiently to show a hydrogen wave 5 mm high at −1.72 v. This wave was followed by a single wave, or a pair of partially merged waves, which rose slowly to a diffusion current. This rise occupied the region from −1.9 to −2.4 v. If these are separate waves, they have inflection points at −2.03 and −2.22 v, and heights of 12 and 9 mm, respectively. They decreased in height rapidly and disappeared completely in 24 hours. Hence at equilibrium there is little or no lactide present.

[10] The calcium *d*-lactate was furnished by George Ward, Bureau of Agricultural Chemistry and Engineering, U. S. Department of Agriculture.

During the first 24 hours the hydrogen wave increased to a maximum of 41 mm and decreased slowly thereafter. The pronounced maximum associated with the hydrogen wave of lactic acid prepared from both calcium *d*-lactate and commercial lactic acid was not observed in the polarogram of the acid obtained from lactide. Wave *A* and the −2.8-v wave given by lactic acid failed to appear.

### 3. GLYCERIC ACID[11]

The freshly prepared solution of glyceric acid showed only the hydrogen wave with a pointed maximum (fig. 2) and an inflection point estimated to be at −1.81 v. During the course of 24 hours, the height of this wave increased from 50 mm to 53 mm. This increase, although small, may be analogous to the increase noted for glycolic acid and may be caused by the same type of reaction. The polarogram for the freshly prepared solution of glyceric acid also revealed a pointed maximum at −2.75 v, about 12 mm high, which did not change appreciably on standing. This maximum may have been caused by an impurity or by a condensation product, such as glycerylglyceric acid. After 453 hours, wave *A* appeared, 2 mm high, while the hydrogen wave had decreased to 26 mm.

### 4. *d*-ERYTHRONO-γ-LACTONE[12]

A 0.01 *M* solution of *d*-erythrono-γ-lactone in 0.1 *M* tetraethylammonium chloride gave a wave 60 to 70 mm high, with an inflection point at −2.65 v, which changed very little in the course of 457 hours. A small hydrogen wave at −1.70 v appeared after about 96 hours and grew in the course of 457 hours to a height of 4 mm.

### 5. *l*-THREONO-γ-LACTONE[13]

The polarographic curve obtained with a 0.01 *M* solution of *l*-threono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 2) was similar to that obtained with *d*-erythrono-γ-lactone except that the lactone wave appeared at −2.54 v with a small rounded maximum instead of at −2.65 v. After 453 hours the hydrogen wave had not appeared but wave *A*, 1 mm high, was present at −1.13 v. This shows that a part of the lactone had been hydrolyzed and utilized in the "oxygen-mercury" reaction.

### 6. *l*-ARABONO-γ-LACTONE [15]

A 0.01 *M* solution of *l*-arabono-γ-lactone in 0.1 *M* tetraethylammonium chloride gave a wave 60 mm high at −2.60 v, which decreased to 40 mm in 457 hours. In the course of 28 hours, a hydrogen wave 1 mm high appeared at −1.74 v. There is no evidence of the formation of a wave which could be ascribed to the delta lactone. After 120 hours, wave *A* appeared at −1.13 v, at the expense of the hydrogen wave.

[11] The glyceric acid used in the investigation was a commercial liquid product from the firm of C. A. F. Kahlbaum.
[12] The crystalline lactone was furnished by J. E. Glattfeld, University of Chicago.
[13] The crystalline lactone was furnished by Chas. Pfizer & Co.

### 7. *l*-RIBONO-γ-LACTONE [16]

A 0.01 *M* freshly prepared solution of *l*-ribono-γ-lactone in 0.1 *M* tetraethylammonium chloride gave a wave 61 mm high with a rounded maximum at −2.44 v. In the course of 457 hours, the wave decreased to 40 mm without a maximum while a hydrogen wave 2 mm high appeared at −1.80 v. After 193 hours a very small wave *A* at −1.2 v was present.

### 8. *d*-XYLONO-γ-LACTONE [5]

A freshly prepared 0.01 *M* solution of *d*-xylono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 8) gave a wave at −2.48 v, 68 mm high, which decreased in 453 hours to 18 mm. As this wave became smaller, its inflection point shifted to more negative values, reaching −2.56 v in 453 hours. In the course of 24 hours, a hydrogen wave appeared at −1.76 v, and reached a height of 20 mm in 194 hours, when it appeared to be the result of the merging of two waves of approximately equal heights. Wave *A* appeared at −1.1 v in the course of about 100 hours and increased to a height of 7 mm in 453 hours.

### 9. *d*-LYXONO-γ-LACTONE [17]

A freshly prepared 0.01 *M* solution of *d*-lyxono-γ-lactone in 0.1 *M* tetraethylammonium chloride showed a single large wave with a very erratic diffusion current. The inflection point was estimated to be at −2.6 v and the height about 60 mm. Close examination of the initial current increase indicated the possible presence of a wave several mm high at −2.3 v. The presence of this small wave became more obvious in polarograms taken at later times, but even after 453 hours it was not clearly separated from the beginning of the lactone wave. After 453 hours the lactone wave had decreased to a height of about 30 mm. A hydrogen wave, as such, failed to appear although hydrolysis of the lactone must have occurred, since wave *A* appeared 139 hours after mixing the solution and at 453 hours had become 2 mm high. The curves obtained were much like those from *d*-gulono-γ-lactone except for the more erratic diffusion current.

### 10. *l*-RHAMNONO-LACTONES [15]

The polarogram of a freshly prepared 0.01 *M* solution of *l*-rhamnono-δ-lactone in 0.05 *M* lithium chloride showed a wave about 60 mm high at −2.15 v. This wave disappeared in the course of 24 hours, and a hydrogen wave appeared at −1.77 v. The latter wave reached a height of 45 mm in 24 hours and did not change further in 235 hours.

A freshly prepared 0.01 *M* solution of *l*-rhamnono-δ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 8) gave a lactone wave at −2.30 v with a rounded maximum and a diffusion current corresponding to a height of about 35 mm. The lactone wave disappeared in the course of 21 hours, and a hydrogen wave appeared at −1.80 v. Obviously the delta lactone is hydrolyzed rapidly, and the equilibrium state for the acid-lactone mixture does not contain an appreciable quantity of the delta lactone. In the course of time the hydrogen wave developed a maximum and passed through the stages described more fully on page 103, and shown in figure 8. The hydrogen

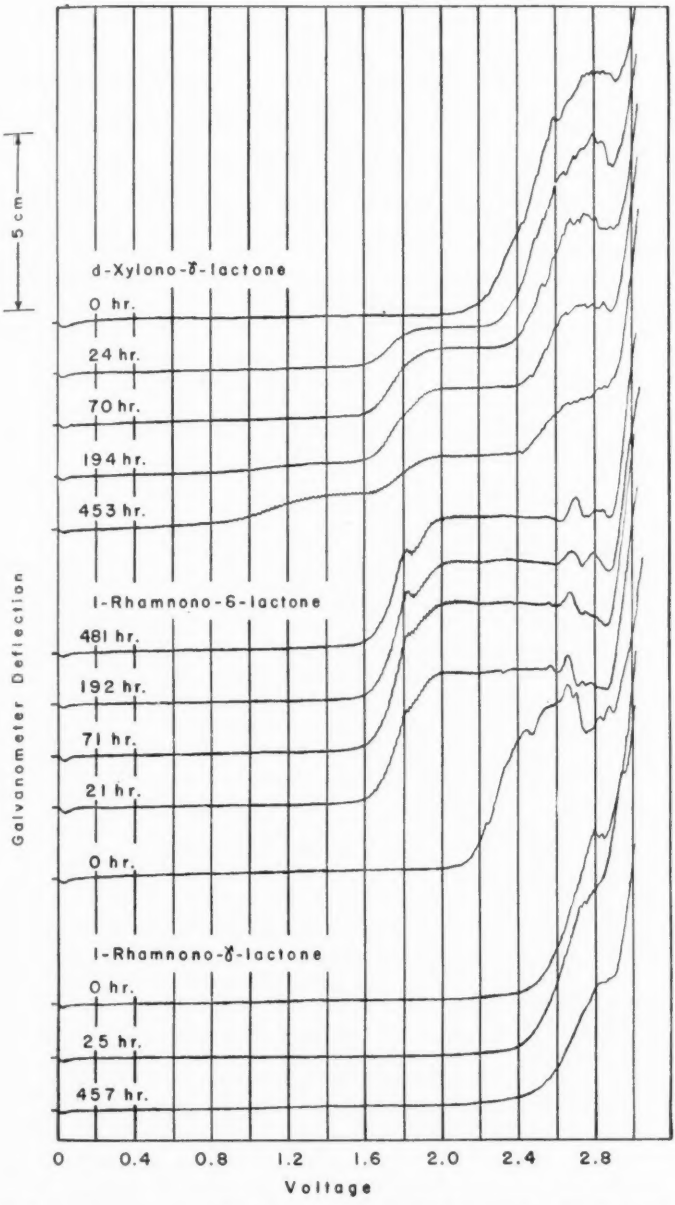



FIGURE 8.—*Polarograms which show the effect of time upon 0.01 M solutions of d-xylono-γ-lactone, l-rhamnono-δ-lactone, and l-rhamnono-γ-lactone in 0.1 M tetraethylammonium chloride.*

wave was 37 mm high at 21 hours and reached a maximum height of 39 mm at 169 hours, after which it decreased in height to 36 mm at 481 hours. Presumably, the decrease in the hydrogen wave is caused by the formation of the gamma lactone, which is indicated by a small rise in the curve in the vicinity of −2.8 v, the approximate potential of the gamma lactone wave. All of the polarograms for this sample showed a small wave at −2.65 v, which did not change with time and is assumed to have been caused by some impurity.

A freshly prepared 0.01 *M* solution of *l*-rhamnono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 8) showed only a single wave 45 mm high, at −2.68 v. In the course of 457 hours, the height of the wave decreased slowly to 35 mm. A comparison of the polarograms obtained from solutions of the gamma and delta lactones of *l*-rhamnonic acid, after standing nearly 500 hours, reveals that the solution prepared from the delta lactone contained largely free *l*-rhamnonic acid and very little gamma lactone, whereas the solution prepared from the gamma lactone contained largely unchanged gamma lactone and very little free *l*-rhamnonic acid. Under the conditions of this experiment, and in similar experiments with 0.05 *M* lithium chloride, equilibrium is not even approached in 500 hours.

### 11. *d*-GLUCONIC ACID AND ITS LACTONES [15]

It may be observed from the curves already given in figure 1 that in the lithium chloride environment 0.01 *M* *d*-gluconic acid and its delta and gamma lactones give well-defined waves which change with time in a very characteristic manner. A freshly prepared 0.01 *M* solution of *d*-gluconic acid in 0.05 *M* LiCl gave only a hydrogen wave at −1.80 v, 68 mm high, which decreased to 52 mm in 235 hours. The freshly dissolved delta and gamma lactones in the same environment gave waves 52 mm high at −2.03 and −2.01 v, respectively. The two waves appeared much the same, and in the absence of further observation they would have been mistaken for one and the same wave. But the changes which took place when the solutions were allowed to stand show very clearly that the waves are entirely different. The wave for the delta lactone decreased rapidly and disappeared entirely in the course of 24 hours, while a hydrogen wave appeared at −1.77 v. These changes indicate that the delta lactone and the free acid establish equilibrium quickly. In fact, after 24 hours the polarograms for the solutions prepared from the delta lactone and from the acid are almost identical. The absence of a detectable delta lactone wave after several hours shows that a 0.01 *M* solution of *d*-gluconic acid equilibrated at 25° C does not contain an appreciable quantity of *d*-glucono-δ-lactone.

The polarograms for the solution prepared from the gamma lactone changed with time much more slowly than those for the delta lactone, and the changes followed an entirely different course. The solution of the gamma lactone, after standing 24 hours, showed three waves with a total height of 53 mm—one at −1.71 v, 24 mm high; one at −2.08 v, 4 mm high; and one at −2.22 v, 25 mm high. The −1.71-v hydrogen wave may be attributed to the acid set free by hydrolysis of the lactone and needs no further explanation; but the presence of two waves in the region originally

occupied by the gamma lactone wave requires consideration. The −2.22-v wave may be assigned to the gamma lactone, because measurements at frequent intervals during a 235-hour period revealed a gradual decrease in the height of the wave and a movement towards a more negative potential. This shift in potential of the wave may be caused by the change in the environment incident to the increase in acidity. The small wave at −2.08 v (which moved to −2.03 v before disappearing) may be caused by a condensation product or other substance produced from the gamma lactone during the course of the hydrolysis. The reality of the −2.08-v wave is supported by the existence of similar waves in the polarograms obtained by using the tetraethylammonium chloride environment. When the solution was allowed to stand, the −2.08-v wave decreased in height and disappeared completely in about 120 hours. This shows that the concentration of the substance, whatever it may be, decreases until at equilibrium it is scarcely detectable. In the polarogram obtained at 235 hours, the gamma lactone wave is detectable but poorly defined and about 3 mm high, and the hydrogen wave is about 43 mm high. Thus it appears that the 0.01 *M* equilibrated solution of *d*-glucono-γ-lactone contains for the most part the free acid with a small quantity of the gamma lactone and very little, if any, delta lactone.

As may be seen by comparing the curves of figures 1, 4, 5, and 9, the polarograms for *d*-gluconic acid and its lactones in the tetraethylammonium chloride environment are similar to those obtained in the presence of lithium chloride, but differ from the latter as the waves appear at slightly more negative potentials and usually show pointed maxima and erratic diffusion currents.

A freshly prepared 0.01 *M* solution of *d*-gluconic acid in 0.1 *M* tetraethylammonium chloride (fig. 9) showed only a −1.80-v hydrogen wave about 55 mm high, with a pointed maximum. The height of the hydrogen wave decreased in the course of 457 hours to 12 mm. Probably because the maximum decreased more rapidly than the diffusion current, this hydrogen wave appeared, after 193 hours, to be two partially merged waves; but at 457 hours it appeared quite normal. Wave *A* at −1.12 v, first detected at 48 hours, increased in height to 7 mm at 457 hours. At 457 hours a small rounded maximum appeared at −2.35 v and seemed to indicate a small wave, probably due to *d*-glucono-γ-lactone.

A 0.01 *M* solution of *d*-glucono-δ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 9), 6 minutes after mixing, gave a wave at −2.16 v, 33 mm high, which appeared to have a rounded maximum partly merged with a wave at about −2.33 v, perhaps 7 mm high, rising slowly to the diffusion current. It may be that the two waves are parts of a single wave consisting of a maximum superposed on the inflection point. The delta lactone in the dilute aqueous solution was hydrolyzed rapidly, as shown by the presence of a small hydrogen wave at −1.73 v only 6.5 minutes after the lactone was dissolved, and by the fact that the polarogram at the end of 3½ hours was substantially identical with that of a similar freshly prepared solution of *d*-gluconic acid in the same environment.

A 0.01 *M* freshly prepared solution of *d*-glucono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 9) showed only a wave at −2.16 v, 40 mm high. After 4.5 hours the wave was unchanged; in 27 hours it had decreased to 33 mm and continued to decrease until at 457 hours

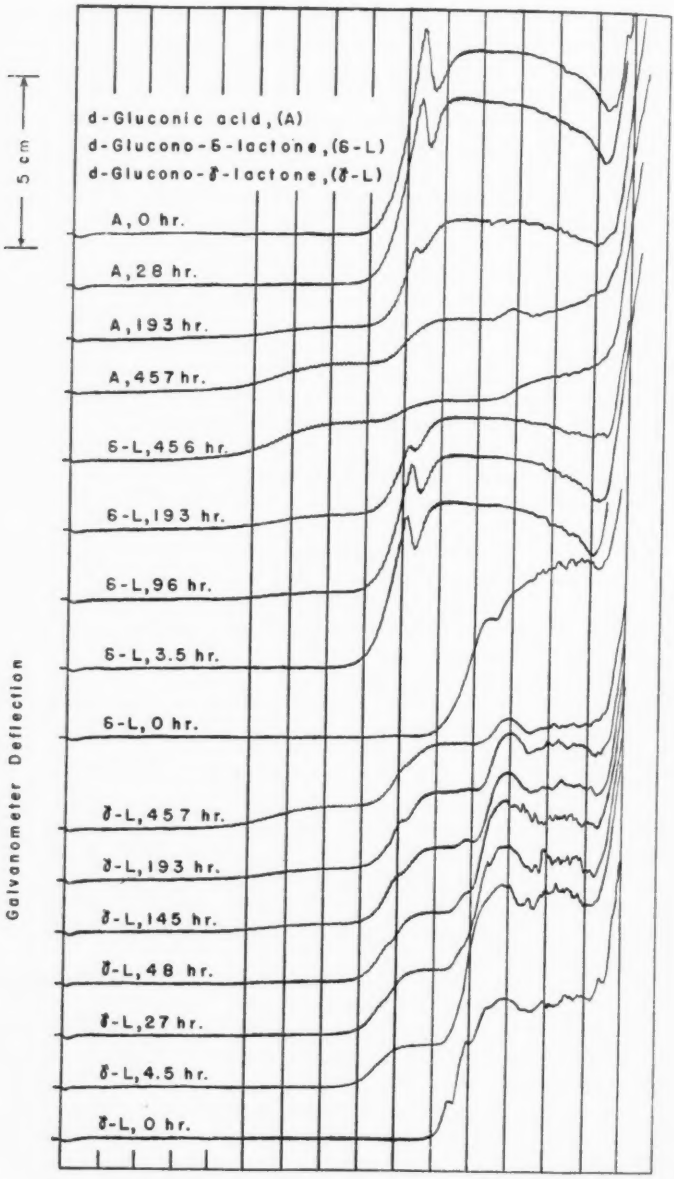



FIGURE 9.—*Polarograms for d-gluconic acid, d-glucono-δ-lactone, and d-glucono-γ-lactone, 0.01 M, in 0.1 M tetraethylammonium chloride.*

The curves for the lactones are not strictly comparable with those of figures 4 and 5 because different capillaries were used in the two cases.

it showed only as a rounded maximum 5 mm high without an appreciable diffusion current. At 48 hours this wave appeared to have moved from −2.16 to −2.25 v, while a definite wave 6 mm high became visible at −2.12 v. The shift in the potential of the gamma lactone wave and the appearance of a new wave at a slightly less negative potential parallels the changes which were found in the polarograms obtained with lithium chloride environmental solutions. The −2.2-v lactone wave gradually decreased and was scarcely detectable at 193 hours. It may well be that the −2.16-v wave found in the freshly prepared solution is composed of two waves at −2.12 and −2.25 v which are resolvable as they become smaller. The hydrogen wave appeared shortly after the solution was prepared; at 4.5 hours it was 12 mm high at −1.72 v; at 27 hours it was 18 mm high and appeared to be composed of two waves, partly merged, at −1.70 and −1.82 v. At 48 hours the composite wave was unchanged in appearance and 20 mm high; it decreased to 18 mm at 457 hours and still gave the appearance of a pair of partially merged waves. Wave *A* appeared at 145 hours and increased to 10 mm at 457 hours. The results clearly show that *d*-glucono-γ-lactone is hydrolyzed less rapidly than d-glucono-δ-lactone, but more rapidly than any of the other gamma lactones studied.

### 12. *d*-GALACTONIC ACID AND ITS GAMMA LACTONE [15]

The polarogram obtained with a freshly prepared 0.01 *M* solution of crystalline anhydrous *d*-galactonic acid in 0.1 *M* tetraethylammonium chloride (fig. 10) showed only a −1.80-v hydrogen wave, 64 mm high, with a pointed maximum. In the course of 167 hours the hydrogen wave decreased, and the maximum was suppressed so as to give the effect of two waves. After 456 hours, the free acid appeared to have been entirely neutralized, and the hydrogen wave had been replaced by wave *A* at −1.1 v, 6 mm high. In addition to wave *A*, there appeared to be a wave at −2.28 v, with a rounded maximum, and also a poorly developed wave about 20 mm high at −2.66 v. The latter matched the wave for *d*-galactono-γ-lactone and was probably caused by that substance. The results indicate that a 0.01 *M* solution of *d*-galactonic acid at equilibrium contains an appreciable quantity of the gamma lactone, and perhaps an unidentified substance.

The polarogram for a freshly prepared 0.01 *M* solution of *d*-galactono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 10) gave a wave 36 mm high at −2.62 v and also a very small wave at −2.15 v. The latter wave, which was perhaps 2 mm high, was noticeable in the polarogram taken after 24 hours but disappeared in the course of 48 hours. Possibly this wave was caused by the presence of a small quantity of impurity in the sample. The gamma lactone wave at −2.62 v decreased in the course of 452 hours to 25 mm. A small hydrogen wave at −1.70 v appeared in the polarograms taken from 48 to 191 hours after preparation of the solution, and was absent at 452 hours. The disappearance of the hydrogen wave may be attributed to the neutralizing action of the mercury in the presence of traces of oxygen, since wave *A* appeared at 452 hours, 2 mm high.

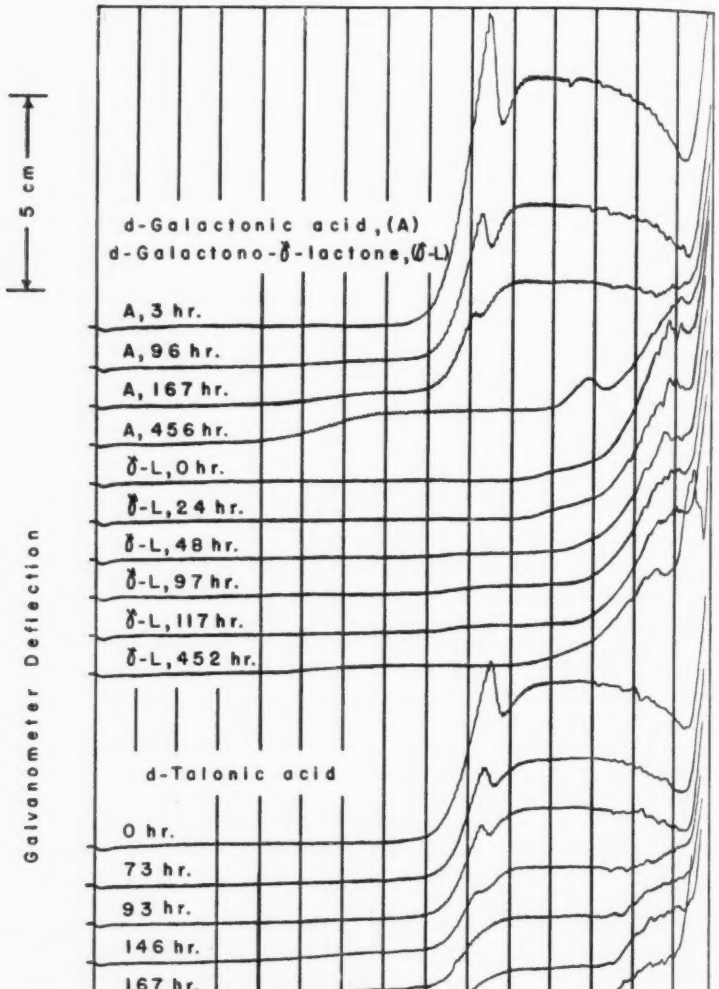



FIGURE 10.—*Polarograms which show the effect of time on solutions of 0.01 M d-galactonic acid, d-galactono-γ-lactone, and d-talonic acid in 0.1 M tetraethylammonium chloride.*

### 13. *d*-MANNONO-LACTONES [15]

The polarogram for a freshly prepared 0.01 *M* solution of *d*-mannono-δ-lactone in 0.1 *M* tetraethylammonium chloride gave a single wave approximately 50 mm high at about −2.4 v. After 1.3 hours this delta lactone wave had not changed appreciably and there was no evidence of the hydrogen wave, but after 24 hours the solution gave the hydrogen wave at −1.75 v, 23 mm high, and the delta lactone wave had entirely disappeared. Apparently, even at 25° C the delta lactone in 0.01 *M* solution is hydrolyzed in the course of 24 hours and is not present in detectable quantity in the equilibrated solution. The lack of a hydrogen wave in the polarogram taken after 1.3 hours shows that hydrolysis begins slowly, as might be expected in a neutral solution. A wave, supposedly caused by the gamma lactone, appeared at −2.60 v, and reached a height of 12 mm in 429 hours.

The polarogram for the freshly prepared 0.01 *M* solution of *d*-mannono-γ-lactone in 0.1 *M* tetraethylammonium chloride showed a wave 50 mm high at −2.65 v. When the solution was allowed to stand, the lactone wave did not change appreciably in spite of the fact that after 48 hours a small hydrogen wave appeared at −1.74 to −1.78 v and increased to a height of 3 mm in 451 hours.

### 14. *d*-TALONIC ACID AND ITS GAMMA LACTONE [18]

The polarograms for *d*-talonic acid in 0.1 *M* tetraethylammonium chloride (fig. 10) show that, even in dilute aqueous solution, the free acid changes relatively quickly into the corresponding lactone. A freshly prepared 0.01 *M* solution of *d*-talonic acid gave only a single wave (with pointed maximum) at −1.82 v, 40 mm high. When the solution was allowed to stand, the heights of both the wave and the maximum decreased, the latter more rapidly than the former, so that at 146 hours the wave had the appearance of two partially merged waves. At 167 hours the acid wave had decreased to 17 mm and a wave (supposedly caused by the gamma lactone) had appeared at −2.6 v, 8 mm high. At 429 hours the acid wave had disappeared entirely and the lactone wave had increased to a height of 24 mm and had shifted to −2.48 v. In addition to the waves enumerated, wave *A* appeared in the course of 146 hours and increased to a height of 3 mm at 429 hours. As mentioned before, wave *A* indicates a reaction between dissolved oxygen, mercury, and the sugar acid.

A freshly prepared 0.01 *M* solution of *d*-talono-γ-lactone in 0.1 *M* tetraethylammonium chloride gave only a single wave with a very high sharp maximum which in a less readily reduced environment would have shown a diffusion current perhaps 50 mm high with an inflection point at about −2.5 v. The lactone wave did not change markedly with time, but after 24 hours a small hydrogen wave appeared at −1.75 v and at 429 hours had increased to 8 mm. On account of a very erratic diffusion current, the height of the γ-lactone wave could not be estimated.

### 15. *d*-GULONO-γ-LACTONE [19]

The polarogram obtained with a freshly prepared 0.01 *M* solution of *d*-gulono-γ-lactone in 0.1 *M* tetraethylammonium chloride showed only a wave at −2.60 v. For the first 117 hours the height of this

lactone wave was of the order of 50 mm, after which it decreased slowly to 38 mm at 453 hours. Wave *A* at −1.15 v was first noticeable at 117 hours and increased slowly to 1 mm at 453 hours. The marked stability of this lactone is shown by the absence of the hydrogen wave in the polarograms obtained over a long period of time. However, the decrease in height of the lactone wave and the appearance of wave *A* show that some hydrolysis of the lactone occurred.

### 16. *l*-ALLONO-γ-LACTONE [20]

The polarogram for a freshly prepared 0.01 *M* solution of *l*-allono-γ-lactone in 0.1 *M* tetraethylammonium chloride gave only a wave at −2.52 v, 58 mm high, which decreased to 43 mm in 453 hours. A hydrogen wave at −1.75 v appeared shortly after the lactone was dissolved; it was 4 mm high in 24 hours and increased to 11 mm in 453 hours.

### 17. *d*-α-GALAHEPTONO-γ-LACTONE [21]

A freshly prepared 0.01 *M* solution of *d*-α-galaheptono-γ-lactone in 0.1 *M* tetraethylammonium chloride showed only a wave starting at −2.5 v and rising very irregularly off scale. At 25 hours there was an irregular diffusion current with a wave height of 45 mm and an inflection point at approximately −2.65 v. The compound is configurationally related to *l*-mannono-γ-lactone and resembles it in stability towards hydrolysis. The height of the lactone wave did not change appreciably in 457 hours, although a hydrogen wave approximately 1 mm high appeared at −1.78 v.

### 18. *d*-α-GLUCOHEPTONO-γ-LACTONE [22]

A freshly prepared 0.01 *M* solution of *d*-α-glucoheptono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 11) gave a single wave at −2.56 v, about 45 mm high. The −2.56-v wave appeared to start with a slow rise in current at −2.2 v. In the course of time, this early rise was resolved into a wave at −2.3 v with a maximum and a diffusion current of about 5 mm. Simultaneously the potential for the −2.56-v wave shifted to −2.64 v, and a −1.72-v hydrogen wave appeared and grew in 459 hours to a height of 13 mm. The cause of the wave at −2.3 v is not known, but it has been mentioned previously that many of the aldonic acids and lactones give small waves near this voltage. When these observations were repeated, using a freshly recrystallized sample and the constant-level capillary, the −2.3-v wave failed to develop a maximum and the hydrogen wave, after appearing at 19 hours, was replaced by wave *A*.

### 19. *d*-β-GLUCOHEPTONO-γ-LACTONE [23]

A freshly prepared 0.01 *M* solution of *d*-β-glucoheptono-γ-lactone in 0.1 *M* tetraethylammonium chloride showed only a single wave at −2.53 v about 57 mm high. In the course of 459 hours the inflection point of the wave shifted to −2.57 v, and the height decreased to 47 mm. Even on long standing the solution did not show a hydrogen wave, and hence the lactone is relatively stable towards hydrolysis. This stability seems peculiar inasmuch as the configuration of the lactone is similar to that of *d*-glucono-γ-lactone, which hydrolyzes readily.

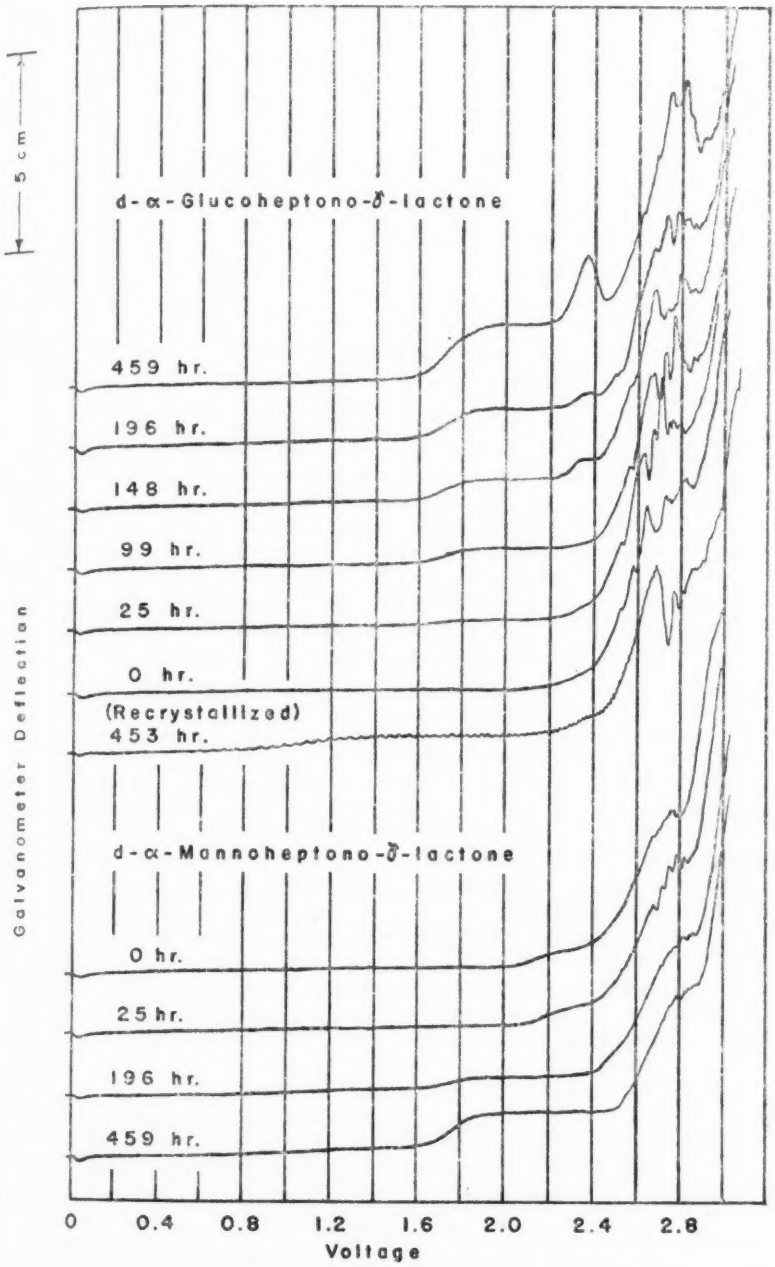



FIGURE 11.—*Polarograms for 0.01 M d-α-glucoheptono-γ-lactone and d-α-mannoheptono-γ-lactone in 0.1 M tetraethylammonium chloride.*

The recrystallized sample of *d-α*-glucoheptono-γ-lactone was run with the constant-level capillary. As a result the curve is comparable only qualitatively with the other curves of the group.

When these observations were repeated, using a freshly recrystallized sample and the constant-level capillary, the curvature of the initial rise due to the gamma lactone wave suggested the presence of a small wave at −2.3 v, which persisted unchanged throughout the period of observation (453 hours).

### 20. *d*-α-MANNOHEPTONO-γ-LACTONE [24]

The freshly prepared 0.01 *M* solution of *d*-α-mannoheptono-α-lactone in 0.1 *M* tetraethylammonium chloride (fig. 11) gave a wave about 34 mm high which appeared to be the main gamma lactone wave with an inflection point at −2.6 v. The freshly prepared solution also showed a 4-mm wave at about −2.16 v. In the course of time, the height of the −2.16-v wave decreased, and the potential shifted to −2.4 v, while the main wave became steeper and the inflection point shifted to −2.64 v. The −2.16-v wave disappeared in 168 hours. The height of the −2.64-v wave at 459 hours was 27 mm. A hydrogen wave at −1.77 v appeared in about 48 hours and grew to 7 mm in 459 hours. The −2.16-v wave in the polarogram for the freshly prepared solution of *d*-α-mannoheptono-γ-lactone suggests that the sample may have contained impurities which were responsible for this unexplained wave. Part of the free acid corresponding to the hydrogen wave may have been formed from the substance originally responsible for the −2.16-v wave, but the increase in the height of the hydrogen wave after this wave had disappeared shows the hydrolysis of the lactone and indicates the presence of appreciable acid in the equilibrium solution.

### 21. *d*-β-MANNOHEPTONIC ACID AND ITS GAMMA LACTONE [25]

A freshly prepared 0.01 *M* solution of *d*-β-mannoheptonic acid in 0.1 *M* tetraethylammonium chloride gave only a hydrogen wave 55 mm high, at −1.82 v, with a pointed maximum. When the solution was allowed to stand, the height of the hydrogen wave decreased and, since the maximum decreased more rapidly that the diffusion current, at 169 and 196 hours it had the appearance of two partially merged waves. The lactone wave was detected after about 170 hours, at which time it appeared at −2.75 v. In the course of time, this wave grew larger and its inflection point shifted to less negative values, reaching −2.60 v at 429 hours, when there was some indication of a small wave at −2.3 v almost merged with the wave at −2.60 v. At 459 hours the hydrogen wave had disappeared entirely, the lactone wave had grown to 26 mm, and wave *A*, which appeared at 48 hours, had grown to 6 mm.

A freshly prepared 0.01 *M* solution of *d*-β-mannoheptono-γ-lactone in 0.1 *M* tetraethylammonium chloride showed only a wave at −2.50 v, about 53 mm high. When the solution was allowed to stand, the height of this wave decreased slowly and the inflection point shifted toward more negative values. After 459 hours the lactone wave was at −2.56 v, 32 mm high. The hydrogen wave and the −2.3-v wave did not appear, but at 459 hours wave *A*, 1 mm high, showed at −1.15 v. It is noteworthy that the potential of the gamma lactone wave observed for this solution shifts toward more negative values as the wave height decreases, whereas the potential of the gamma lactone wave observed in the solution prepared from *d*-β-mannoheptonic acid

shifts toward less negative values as the wave height increases. Thus the polarographic behavior of the lactone is consistent with the behavior of the acid. Shifts are also found in the waves for the lactones and acids of the configurationally related *d*-talonic and *d*-α-guloheptonic acids. Shifts in the potentials of the inflection points of the gamma lactone waves were observed in other instances, but the phenomenon does not appear to be characteristic of the gamma lactones of all aldonic acids. Frequently the determination of the inflection point is somewhat complicated by the presence of the −2.3-v wave, which merges into the gamma lactone wave and makes the measurement uncertain.

### 22. *d*-α-GULOHEPTONIC ACID AND ITS GAMMA LACTONE [26]

A freshly prepared 0.01 *M* solution of *d*-α-guloheptonic acid in 0.1 *M* tetraethylammonium chloride (fig. 12) showed only a wave at −1.80 v with a pointed maximum 53 mm high. When the solution was allowed to stand, the height of this wave decreased to zero, while wave *A* appeared at −1.18 v after 47 hours and grew to a height of 4 mm at 458 hours. A wave developed slowly in the region from −2.6 to −2.8 v. At 458 hours, this wave appeared to be composed of two waves with a total height of 33 mm. One of these waves appeared to be the gamma lactone wave with an inflection point at −2.6 v and the other, the −2.3-v wave of unknown origin.

A freshly prepared 0.01 *M* solution of *d*-α-guloheptono-γ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 12) showed a wave which began at −2.1 v and went off scale. From later curves it seems certain that this is due to two adjacent waves, the second of which, at approximately −2.5 v, has a large maximum. This maximum becomes less pronounced in the course of time and is not noticeable at 143 hours. The first wave appeared to have its inflection point at −2.3 v and to be 25 mm high in the freshly prepared solution. At 94 hours the height of the −2.3-v wave had decreased to 15 mm, and at 121 hours it had merged with the −2.5-v wave, which had become measurable at 94 hours. The sum of the heights of the two waves was 52 mm at 121 hours and decreased to 38 mm at 458 hours. Wave *A* appeared at 143 hours and grew to 2 mm at 458 hours. The appearance of wave *A* and the decrease in the height of the gamma lactone wave indicate hydrolysis of the lactone; but since the hydrogen wave failed to appear, any acid formed by hydrolysis of the lactone must have reacted further to give the substance responsible for wave *A*. The interpretation of the −2.3-v wave must await further investigation.

### 23. *d*-β-GULOHEPTONIC ACID [26]

A freshly prepared 0.01 *M* solution of *d*-β-guloheptonic acid in 0.1 *M* tetraethylammonium chloride showed only a hydrogen wave at −1.78 v, with a pointed maximum. This wave was 57 mm high initially and decreased with time until after 457 hours it was not detectable. At 169 hours a wave began to develop in the region of −2.6 v; at 191 hours it was at −2.65 v and was 9 mm high; at 457 hours it extended from −2.45 to −2.80 v and was 18 mm high. Since the −2.6-v wave occurs in the region characteristic of the gamma lactones, it probably is caused by *d*-β-guloheptono-γ-lactone,

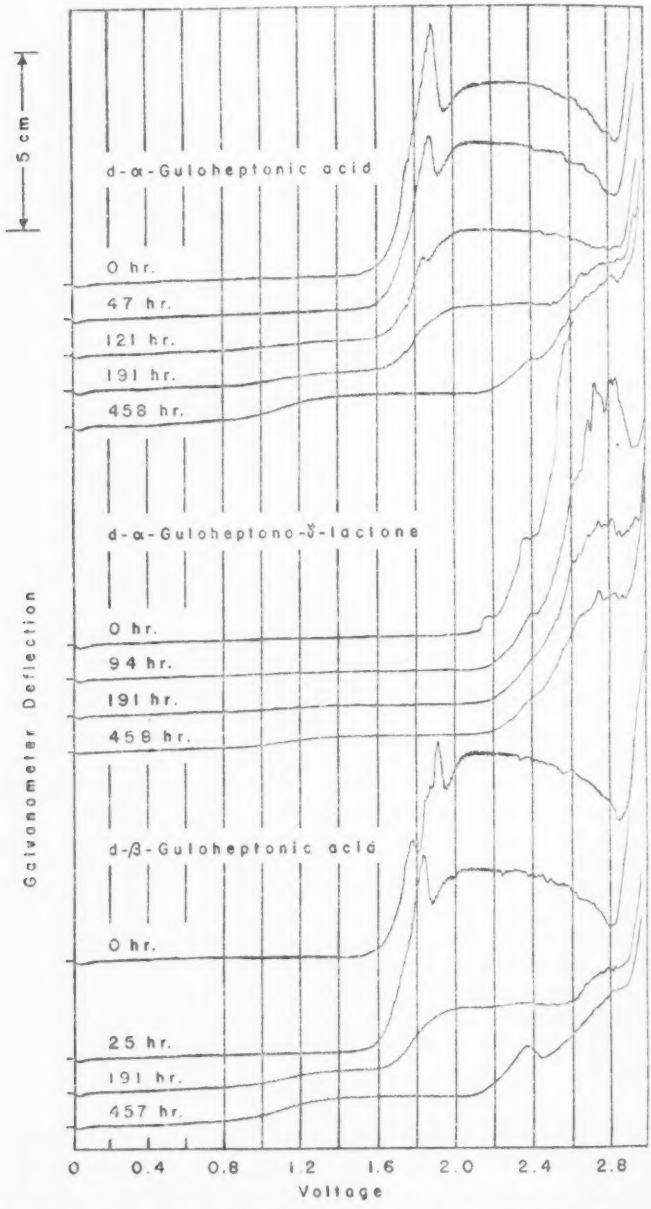



FIGURE 12.—*Polarograms which show the effect of long standing, at room temperature, on 0.01 M solutions of d-α-guloheptonic acid, d-α-guloheptono-γ-lactone, and d-β-guloheptonic acid in 0.1 M tetraethylammonium chloride.*

a sample of which was not available for comparison. In addition to the waves just described, wave *A* at −1.13 v appeared after 47 hours and grew to 5 mm at 457 hours. Also, a −2.2-v wave 7 mm

high appeared at 457 hours. The cause of the −2.2-v wave, which exhibited a rounded maximum, is not known, but it seems probable that it is related to the −2.3-v waves of unknown origin found for many of the polyhydroxy acids.

### 24. LACTOBIONO-δ-LACTONE [27]

A freshly prepared 0.01 *M* solution of lactobiono-δ-lactone in 0.1 *M* tetraethylammonium chloride (fig. 2) showed a lactone wave at −2.16 v, 36 mm high, and a hydrogen wave at −1.74 v, 4 mm high. When the solution was allowed to stand, the lactone wave decreased rapidly as the hydrogen wave increased. At 25 hours the lactone wave was not detectable, and the hydrogen wave had grown to 53 mm, with a pointed maximum. No further change was observed in 459 hours. The presence of a small hydrogen wave only 3 minutes after dissolution of the lactone and the disappearance of the lactone wave within 25 hours show that the lactone is hydrolyzed rapidly and that the equilibrium solution does not contain an appreciable quantity of lactobiono-δ-lactone. A pointed maximum at −2.7 v, 30 mm high with little, if any, diffusion current was observed in the freshly prepared solution. In 25 hours this maximum decreased to about 6 mm, at which height it persisted up to 459 hours. Probably this maximum is caused by some impurity in the sample, possibly a condensation product of lactobionic acid.

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